Dam Removal and Klamath River Water Quality: A Synthesis of the Current Conceptual Understanding and an Assessment of Data Gaps.

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EXECUTIVE SUMMARY

The Klamath River in northern California and southern Oregon supports important runs of anadromous fish species including Coho and Chinook salmon and steelhead trout, as well as resident rainbow trout. The river also supports a variety of other beneficial uses, including recreational uses, water supply uses, cultural uses, and power generation. Poor water quality in the Klamath River currently threatens many of the beneficial uses of the river and is considered to be a major contributing factor in the decline of anadromous salmonid populations from historical levels. In 2008, PacifiCorp, the owner of Iron Gate Dam, Copco 1 and 2 dams, and J.C. Boyle Dam on the middle and upper Klamath River, reached an agreement with several other interested parties to consider dam removal as an approach to restoring salmonid access to spawning and rearing habitat and improving water quality in the river. This report describes our current understanding of the potential water quality impacts of dam removal, presents an assessment of data gaps, and offers a set of conceptual study plans for addressing identified data gaps and improving our understanding of water quality in the Klamath River.

For this synthesis, the potential water quality impacts of dam removal have been considered as either short-term impacts, associated with the process of dam removal and lasting 1–2 years following dam removal, or long-term impacts that represent fundamental changes in riverine dynamics. In the short-term, the most significant impact of dam removal is expected to be increased sediment loads to the middle and lower Klamath River, as sediments trapped behind the dams are released. Based upon recent sediment transport modeling conducted for dam removal studies and assuming the preferred drawdown scenario developed during the modeling runs, short-term high suspended sediment loads are expected in the middle and lower Klamath River following dam removal. Carbon, nitrogen and phosphorus associated with reservoir sediments will also be transported downstream, but as little to no sediment deposition is expected in the river, these nutrients should be well-conserved during transport. Thus, in the short-term, seasonal nutrient availability in the middle and lower Klamath River is not expected to be impacted by dam removal. Toxicity caused by exposure to sediment-associated contaminants is also not expected to be problematic, as recent screening of reservoir sediments indicates low levels of a variety of contaminants (e.g., metals, VOCs, pesticides and herbicides, dioxin). The possibility of short-term sediment deposition in the salt-water mixing zone of the Klamath River estuary requires further study, as deposition has the potential to alter estuarine morphology and the dynamics of mouth closure, which could subsequently affect estuarine water quality and nutrient dynamics.

In the long-term, existing water temperature models for a dam removal scenario indicate that temperatures in the middle and lower Klamath River will be higher during spring and lower during the late summer and fall due to the decreased transit time of water through the Project Reach. The greatest relative warming or cooling is expected to occur just downstream of the lowermost dam (i.e., Iron Gate Dam) with diminished amounts of cooling occurring with distance downstream. Typically negligible amounts of cooling or warming are expected to occur by the mainstem confluence with the Salmon River. The predicted water temperature impacts do not include potential climate change effects, which remain unclear based on our current understanding of factors controlling regional climate. While the long-term impacts of dam removal on the overall nutrient budget of the Klamath River also remain uncertain, the observed seasonal releases of bioavailable nutrients from the reservoirs should be alleviated and reservoir-associated blooms of blue-green algae, including the toxic *Microcystis aeruginosa*, are expected

to significantly decrease or be absent. Incidences of low dissolved oxygen levels, which currently occur on a seasonal basis immediately downstream of the dams, are expected to be reduced or eliminated, as well as incidences of high pH and large diel fluctuations in pH. However, episodic increases in turbidity and suspended solids levels in the middle and lower Klamath River during the late spring and summer may occur in the long-term following dam removal, since the reservoirs will no longer trap suspended algae transported into the river from the upper Klamath Basin. During winter, turbidity and suspended solids associated with storm events are also expected to increase in the middle and lower Klamath River as trapping of mineral sediments by the dams will no longer be supported. Based on their limited active storage capacity, removal of the Project dams is not expected to impact long-term hydrology of the middle and lower Klamath River (not including the Project Reach) on an annual basis. However, seasonal flow variability in the middle Klamath River immediately downstream of Iron Gate Dam is likely to increase, particularly during winter and spring storm events. Within the Project Reach, dam removal will reduce the mean summer hydraulic residence time from approximately several weeks to several days.

Ten conceptual study plans are proposed to address current gaps in our understanding of the effects of dam removal on water quality in the Klamath River. The study plans are designed to supply information supporting informed decision making surrounding dam removal, and to provide baseline data critical for determining the effects of dam removal on the Klamath River and estuary, should the dams eventually be removed. The study plans are conceptual in nature and will benefit from coordination with the Klamath Decommissioning Investigations Group and the larger regulatory and scientific community involved in the current consideration of dam removal.

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1 BACKGROUND AND PURPOSE

The Klamath River traverses approximately 409 km (254 mi), originating in Upper Klamath Lake within the Cascade Mountains of Southern Oregon and flowing southwest through the Northern California Coast range, to its terminus at the Pacific Ocean (Figure 1-1). With an overall watershed area of 40,720 km^2 (approximately 15,722 mi^2), the Klamath River is second only to the Sacramento River on the basis of annual flow volume in California (Kruse and Scholz 2006). It supports important runs of anadromous fish species including Coho and Chinook salmon and steelhead trout, as well as resident rainbow trout (NRC 2004). Major tributaries to the mainstem Klamath include the Williamson River and water diverted from the Lost River in the Lost River Diversion Channel in southern Oregon, and the Shasta, Scott, Salmon, and Trinity Rivers in northern California (Figure 1-1).

The Klamath River is unique to the Pacific Northwest region because the upper-most portion of the watershed is comprised of a low-relief desert plateau, where tributary reaches, including Klamath Marsh and Upper Klamath Lake, exhibit a lower gradient (<0.5%) than the headwaters of other regional major rivers. Downstream of Keno Dam (RM 233.0) to Iron Gate Dam (RM 190.01), the river exhibits an increased river gradient (on the order of 0.8%) (FERC 2007). From Iron Gate Dam to the confluence with the Trinity River (RM 40.0), the slope is fairly constant and more gradual (approximately 0.25%) (Stillwater Sciences 2008). Downstream of the Trinity River, the slope is even more gradual (generally <0.1%). The Klamath Hydroelectric Project (Project), owned by PacifiCorp, generates an average of 716,820 megawatt-hours of electricity annually through the operation of a series of dams located within the high-gradient reaches of the mid-Klamath Basin (FERC 2007). These dams include Keno Dam (RM 233.0), J.C. Boyle Dam (RM 224.7), Copco 1 (RM 198.6) and Copco 2 Dams (RM 198.3), and Iron Gate Dam (RM 190.1) (Figure 1-1). These dams were developed largely for hydropower generation and provide limited storage capacity, mainly in Copco 1 and Iron Gate Reservoirs (total capacity 1.09×10^8 m^3 [88,160 acre-feet], active capacity 1.45×10^7 m^3 [11,749 acre-feet]) (FERC 2007). The Klamath River downstream of Iron Gate Dam and extending to the Klamath River estuary (~RM 4) is unregulated.

Designated beneficial uses occurring in the Klamath River are listed by the California North Coast Regional Water Quality Control Board (NCRWQCB 2006a) and the Oregon Department of Environmental Quality (ODEQ OAR 340-41-0180) (Table 1). ODEQ and NCRWQCB have both included the Klamath River on their corresponding Clean Water Act Section 303(d) lists as a result of observed water quality criteria exceedances.

Table 1. Designated Beneficial Uses in the Klamath River.

Sources: NCRWQCB (2006a) and ODEQ (OAR 340-41-0180).

Middle and/or Lower Klamath River (CA, NCRWQCB [2006a])	Upper Klamath River (OR, ODEQ OAR 340-41-0180)
Municipal and domestic supply (MUN)	Public Domestic Water Supply
Agricultural supply (AGR)	Private Domestic Water Supply
Industrial service supply (IND)	Industrial Water Supply
Industrial process supply (PRO)	Irrigation
Groundwater recharge (GWR)	Livestock Watering
Freshwater replacement (FRSH)	Fish & Aquatic Life
Navigation (NAV)	Wildlife & Hunting
Hydropower generation (POW)	Fishing
Water contact recreation (REC-1)	Boating
Non-contact water recreation (REC-2)	Water Contact Recreation
Ocean, commercial, and sport fishing (COMM)	Aesthetic Quality
Warm freshwater habitat (WARM)	Hydro Power
Cold freshwater habitat (COLD)	Commercial Navigation & Transportation
Wildlife habitat (WILD)	
Rare, threatened, or endangered species (RARE)	
Marine Habitat (MAR)	
Fish migration (MGR)	
Fish spawning (SPAWN)	
Shellfish harvesting (SHELL)	
Estuarine Habitat (EST)	
Aquaculture (AQUA)	
Native American culture (CUL)	

In the upper Klamath Basin, where water from the Klamath River and its tributaries is heavily influenced by agricultural irrigation withdrawals and returns from southern Oregon and northern California, impairments include dissolved oxygen, chlorophyll a, temperature, pH, and ammonia (ODEQ 2004). The entire Klamath River and its tributaries are currently listed as impaired under section 303(d) of the Clean Water Act for temperature, dissolved oxygen, and nutrients (SWRCB 2006, USEPA 2006). Potential sources of impairment include hydroelectric operations, upstream impoundment and flow regulation, among others (SWRCB 2006). The lower Klamath River is also listed for sediment impairment (SWRCB 2006, USEPA 2006) from the Trinity River confluence (RM 40.0) to the estuary mouth (RM 0.0). Lastly, the Klamath River from Copco 1 Reservoir (RM 203.1) to the estuary mouth (RM 0.0) is listed as impaired for toxicity due to the presence of microcystin, a toxin produced by the blue green alga *Microcystis aeruginosa* present in the Project reservoirs (USEPA 2008a–b). Because of potential concerns regarding these water quality impairments and for fish passage considerations, four PacifiCorp dams (Iron Gate, Copco 1 and 2, and J.C. Boyle) are being considered for removal from the Klamath River.

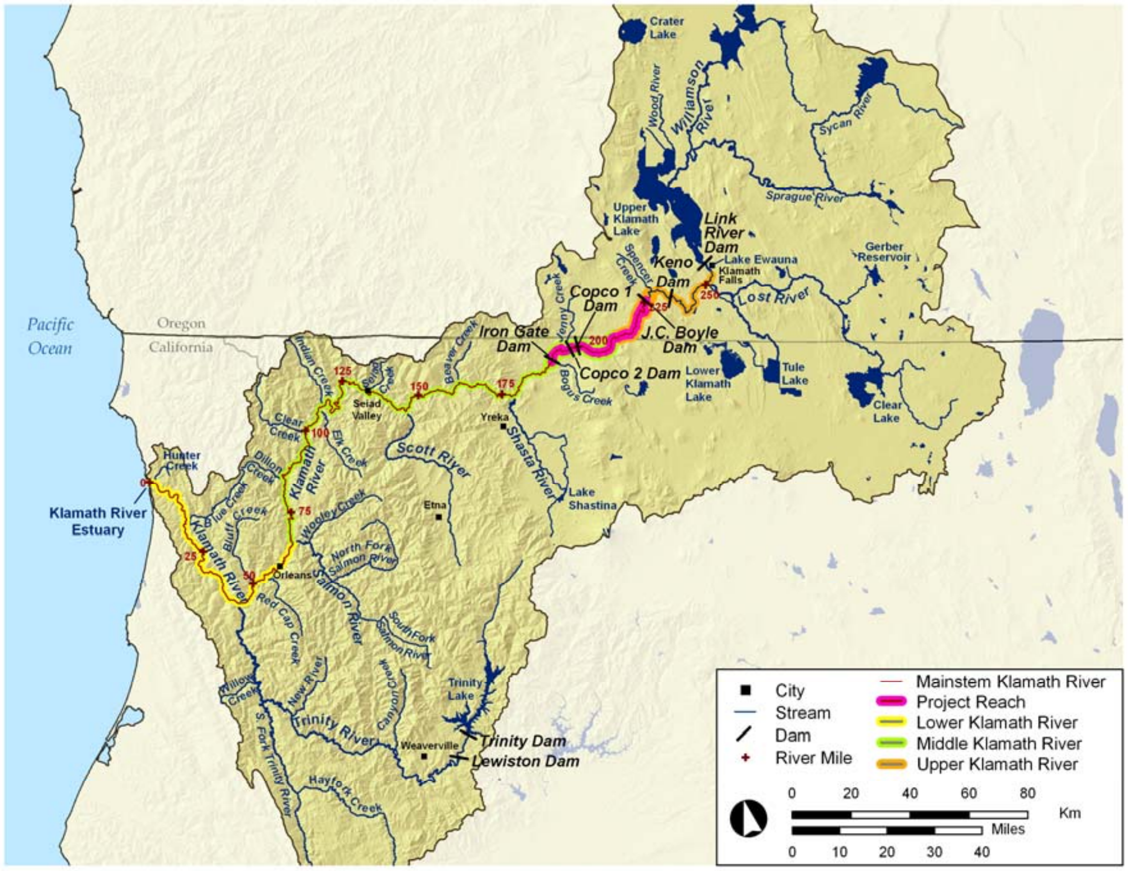

Figure 1-1. Schematic of the Klamath River basin.

As part of the Federal Energy Regulatory Commission (FERC) hydropower relicensing process, PacifiCorp submitted a 401(c) water quality certification application to the State Regional Water Quality Control Board (SWRCB) on March 29, 2006 to describe current impacts to Klamath River water quality from Project operations. The 401(c) application was subsequently withdrawn on July 11, 2008, but PacifiCorp has stated its intention to resubmit the application in the near future (Galusha 2008). A temperature and water quality model developed by PacifiCorp in support of the relicensing effort (PacifiCorp 2005c) was evaluated by NCRWQCB, ODEQ, and the U.S. Environmental Protection Agency (EPA) for applicability to Klamath River TMDL development (Tetra Tech, Inc. 2004). Ultimately, the PacifiCorp model was adopted as the basis for the TMDL model and has since been enhanced in a variety of manners, including modeling of algae dynamics in Lake Euwana, which is located downstream of Upper Klamath Lake. The model simulated the interaction of algae and nutrients with pH in riverine stretches, and included a variety of previously un-modeled algal dynamics (Tetra Tech *in prep*). Once complete, the TMDL process is expected to accomplish the following: 1) identify the maximum load of pollutants the Klamath River is able to assimilate and still fully support its designated beneficial uses; 2) allocate portions of the allowable load to all sources; 3) identify the necessary controls that may be implemented voluntarily or through regulatory means, and; 4) describe a monitoring plan and associated corrective measures to ensure that beneficial uses are fully supported (Tetra Tech *in prep*).

Separate from the FERC re-licensing and the TMDL process, the California State Coastal Conservancy commissioned a series of studies related to dam removal. These studies include 1) estimation of the volume and composition of reservoir sediment deposits (Shannon and Wilson Inc. (2006) and GEC 2006); 2) sediment transport modeling to evaluate potential sediment release during reservoir drawdown should the Project dams be removed (Stillwater Sciences 2008); 3) an analysis of impacts to sensitive fish species associated with sediment release during and after dam removal (Stillwater Sciences 2009), and 4) this report, which provides a water quality synthesis of available information on mechanisms responsible for current water quality conditions in the lower Klamath River and the estuary, and analyzing potential short-term and long-term effects of dam removal on water quality. This report is expected to help inform decision-making regarding potential removal of the four Project dams. While dam removal is expected to result in water quality and fish passage improvements in support of multiple designated beneficial uses on the Klamath River (e.g., REC-1, COMM, WARM, COLD, RARE, MGR, SPAWN, EST, CUL), it will eliminate the hydropower generation (POW) designated beneficial use for the middle Klamath River (Table 1). The Project dams currently produce on average 716,820 MWh annually (FERC 2007). The full implications of dam removal are thus under careful consideration.

Relevant information for this water quality synthesis has been obtained through review of the existing literature as well as coordination with the resource agencies involved in the TMDL process (e.g. EPA Region 9, SWRCB, NCRWQCB) and local tribes. The summary information contained herein is based on numerous studies dating back to the 1970s, and takes advantage of the relatively large amount of nutrient data collected in the Klamath River and its tributaries during the period 2000–2004. Organizations involved in Klamath River water quality data collection include PacifiCorp, US Fish and Wildlife Service (USFWS), the Yaruk, Karuk, and Hoopa Valley Tribes, Quartz Valley Indian Community, US Bureau of Reclamation (USBR), Oregon Department of Environmental Quality (ODEQ), US Geological Survey (USGS), North Coast Regional Water Quality Control Board (NCRWQCB), Department of Water Resources (DWR), and independent researchers.

In addition to general water quality parameters, available information on the myxozoan parasite *Ceratomyxa shasta* (*C. shasta*) and potential impacts of climate change on water quality in the Klamath River and estuary are discussed. Finally, an assessment of data gaps related to dam removal and water quality is presented, followed by recommended conceptual study plans for addressing the identified data gaps.

2 KLAMATH RIVER WATER QUALITY SYNTHESIS

The North Coast Regional Basin Plan (NCRWQCB 2006a) defines the Lower Klamath River Hydrologic Unit as the Klamath River from the mouth (RM 0.0) to the confluence with the Salmon River (RM 66.0) and the Middle Klamath River Hydrologic Unit as the Klamath River from the Salmon River confluence to the Oregon-California border (RM 209.3) (Figure 1-1). The data synthesis contained in this report includes consideration of water quality along the entirety of the *middle* and *lower* Klamath River, where the middle and lower reaches correspond to the NCRWQCB hydrologic unit designations, as well as the *upper* Klamath River, which extends from the Oregon-California border to Lake Euwana (Figure 1-1). The term *Project Reach* refers to the Klamath River from Iron Gate Dam (RM 190.1) to the upstream end of J. C. Boyle Reservoir (RM 228.3), which also includes the remaining two dams proposed for removal (Copco 1 [RM 198.6] and Copco 2 [RM 198.3]). The Project Reach spans the Oregon-California border. Summary characteristics for the four dams located in the Project Reach are presented in Table 2.

Table 2. Summary characteristics of the four Project reservoirs being considered for removal. Source: Table 3-16, FERC (2007).

Reservoir	Year completed	Down-stream RM	Up-stream RM	Maximum total storage (acre-feet)	Maximum active storage (acre-feet)	Average theoretical HRT [a] (days)	Average depth (feet)
J. C. Boyle	1958	224.7	228.3	3,495	1,724	1.1	8.3
Copco 1	1918	198.6	203.1	33,724	6,235	10.7	47
Copco 2	1925	198.3	198.6	73	0	0.0	–[b]
Iron Gate	1962	190.1	196.9	50,941	3,790	14.8	62
Total	–	–	–	88,233	11,839	26.6	–

[a] HRT = hydraulic residence time, calculated by dividing mean annual flow by total storage capacity (FERC 2007).
[b] Depth information for Copco 2 Reservoir is unavailable

Copco 2 Dam is not considered separately in the water quality analysis due to its small volume (70 ac-ft) and extremely short residence time (t_{res}=0.02 d), rendering its effects on Klamath River water quality insignificant compared with JC Boyle, Copco 1, and Iron Gate Reservoirs.

Downstream of the Project Reach, major tributaries to the Klamath River include the Shasta River (RM 176.6), Scott River (RM 143.0), Salmon River (RM 66.0) and Trinity River (RM 40.0). Multiple smaller tributaries also enter the Klamath River along its course to the estuary (Figure 1-1). While land cover in the Klamath River watershed is predominantly forest, rangelands are present throughout the tributary subwatersheds, particularly in the Shasta and Lost River Basins and along several reaches of the middle and upper Klamath River (NRCS 2002). As with most other watersheds in the region, extensive timber harvesting has occurred in the basin, and logging activities continue presently (NRC 2004). Timber harvest in particular has been identified as a significant source of sediment to the middle and lower Klamath River (NRC 2004). The Scott and Shasta River tributary watersheds, along with the entire upper Klamath Basin, possess significant amounts of irrigated cropland. Thus, the Klamath River is potentially impacted by a combination of agriculture, grazing, and forestry practices. Water contact recreation such as whitewater rafting and swimming is common on the Klamath River, both for the general public and for specific tribal activities (NCRWQCB 2006a, Yurok Tribe 2006).

The Klamath River downstream of the Project Reach is populated by a number of anadromous fish, including spring and fall-run Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon

(*O. kisutch*), steelhead trout (*O. mykiss*), coastal cutthroat trout (*O. clarki clarki*), eulachon (*Thaleichthys pacificus*), Pacific lamprey (*Lampetra tridentata*), and green sturgeon (*Acipenser medirostris*) (NRC 2004, Stillwater Sciences 2009). Although historically many of these species were found as far upstream as the Williamson, Sprague, and Wood Rivers upstream of Upper Klamath Lake (NRC 2004), Iron Gate Dam (RM 190.1) currently represents the upstream limit of anadromous species migration along the Klamath River. Populations of most of the anadromous species in the river are reduced from historical levels, and several species, Coho salmon (*Oncorhynchus kisutch*), spring-run Chinook salmon (*O. tshawytscha*), summer-run steelhead trout (*O. mykiss*), eulachon (*Thaleichthys pacificus*), are at populations far below historical levels. Water quality is thought to be a major factor limiting salmonid survival and growth in the Klamath River.

The following sections examine water quality conditions in the Klamath River. For each water quality parameter, we summarize current understanding, present anticipated short-term and long-term effects of dam removal, and identify data gaps requiring further study.

2.1 Hydrology

2.1.1 Current Understanding

Klamath River hydrology has been analyzed and presented by a variety of organizations and individuals, including USGS, Hecht and Kamman (1996), Hardy (1999), USGS (1995, as cited by Hardy 1999), Natural Resources Council (2008) and Gannett et al. (2007). While a brief summary of hydrology in the Klamath River is included below to contextualize the larger water quality discussion, it is beyond the scope of this synthesis to catalog results of previous Klamath River hydrology studies. No further hydrological analysis of the Klamath River dataset (Table 3) has been performed for the water quality analysis.

As is common throughout the region, flows in the Klamath River and its tributaries are lowest during the dry summer months (June through October) and highest during the winter months (November through February). During spring (March through May), flows in the Klamath River are fed by snowmelt from the upper Klamath Basin and higher elevation tributaries, as well as rainfall and groundwater from lower elevation tributaries throughout the basin. As shown in Table **3**, water discharged from Iron Gate Dam (USGS gage # 11516530) in the summertime accounts for approximately 30% of the total flow reaching the Klamath River estuary (USGS gage #11530500), while on an annual basis Iron Gate outflow accounts for just over 10% of total flow.

Table 3. Flow summary for the Klamath River and major tributaries.

Gage Name	USGS Gage No.	Klamath River Mile [1]	Mean Annual Flow m^3/s (cfs,)	Mean August Flow m^3/s (cfs,)	Period of record
Klamath River at Keno Dam	11509500	233	45.8 (1,616)	25.5 (899)	1904–1913, 1929-present
Klamath River below Iron Gate Dam	11516530	190	58.7 (2,073)	27.6 (974)	1960–present
Shasta River near Yreka	11517500	176.6	5.3 (186)	1.1 (39)	1933–present
Scott River near Ft. Jones [3]	11519500	143.0	18.2 (642)	1.7 (61)	1941–present
Klamath River near Seiad Valley	11520500	129	110.0 (3,885)	39.4 (1,390)	1912–1925, 1951–present
Salmon River at Somes Bar	11522500	66.0	51.1 (1,806)	7.4 (261)	1911–1915, 1927–present
Klamath River at Orleans	11523000	59	232.7 (8,218)	57.8 (2,040)	1927–present
Trinity River at Hoopa [2]	11530000	40.0	140.0 (4,944)	22.0 (777)	1963
Klamath River near Klamath	11530500	7	502.3 (17,738)	88.9 (3,140)	1962

[1] River mile of tributary indicates the point at which the tributary enters the mainstem Klamath River. Some gage locations are only known to within one river mile.
[2] The most downstream gage on this tributary is located greater than 15 km (9 mi) upstream of the confluence with the Klamath River.

Water supply to the Klamath River is affected by historical conversion of wetlands to agricultural land uses, irrigation diversions, and importation of water from other basins (Hardy 1999, Hecht and Kamman 1996, USGS 1995 as cited by Hardy 1999). During the spring and summer months, a significant amount of water from the Klamath Basin upstream of J. C. Boyle Dam (RM 224.7) is diverted for irrigation purposes by the Bureau of Reclamation (BOR) Klamath Project. The BOR Klamath Project supplies irrigation water for over 200,000 acres on approximately 1,400 farms locally in Oregon and California, and it includes multiple dams and reservoirs, such as Clear Lake Dam and Reservoir, Tule Lake, Lower Klamath Lake, Gerber Dam and Reservoir, Upper Klamath Lake, Link River Dam, Lost River, Miller, Malone, and Anderson-Rose Diversion Dams (Stene 1994). Although some water is added to the Upper Klamath River via the Lost River Diversion, Hecht and Kamman (1996), USGS (1995), Hardy (1999) and others analyzed available pre- and post-project hydrology for the BOR Klamath Project and the four PacifiCorp Project dams and found that inflows to the Klamath Basin have been significantly reduced since completion of the majority BOR Klamath Project. For example, Hecht and Kamman (1996) compared hydrology in two pre-development years (1913 and 1918) with hydrology in two post-development years (1985 and 1987) having comparable runoff patterns, and found that post-development flows from the Keno gauge (~RM 233) to the mouth (RM 0.0) tended to be lower from May through August and higher from September though November. Since 1962, a small but significant decreasing annual trend in discharge at Iron Gate Dam (-0.09 m^3/s [-3 cfs] per year) has been observed relative to typical flow rates (>28.3 m^3/s [1000 cfs], 95% CI = -0.200 to -0.024 m^3/s [-7 to -0.9 cfs] per year; $P \leq 0.003$) (Bartholow 2005).

Although no studies have analyzed the effects of individual Project dams on either an annual or seasonal basis, the four reservoirs presently have limited active storage and provide minimal flood attenuation for larger peak flood events. Maximum active storage in the four Project reservoirs is less than $1.5x10^7$ m^3 (12,000 acre-feet) (Table 2), or less than 1% of annual runoff to the Klamath River estuary (Table **3**), and only approximately 1% of annual runoff from the upper Klamath River (NRC 2004).

In the lower Klamath basin, contributions from the Shasta and Scott Rivers during summer are also reduced due to both direct withdrawal and losses of accretion flows from groundwater pumping for irrigation (Drake et al. 2000, NRC 2004, NCRWQCB 2006b). Furthermore, the amount of water supplied to the Klamath River by the Trinity River (RM 40.0) decreased from approximately 32% to 26% after the construction of the Trinity River Diversion, which diverts water from the Trinity Watershed near Whiskeytown to the Sacramento River Basin (NRC 2004).

2.1.2 Anticipated Impacts of Dam Removal

2.1.2.1 Short-term Effects

The dam removal process will involve the release of the approximately $1.1x10^8$ m^3 (90,000 acre-feet) (Table 2) of water stored in the four Project reservoirs. Modeling results presented in Stillwater Sciences (2008a) indicate that daily discharge downstream of Iron Gate Dam may be increased by up to 2,500 cfs (70 m^3/s) during the drawdown of Copco 1 and Iron Gate reservoirs. However, this increase, as modeled, will last for less than three weeks in the month of November. Beyond the initial release of stored water from the reservoirs, the short-term effects (1–2 years) of dam removal on hydrology are not likely to differ substantially from long-term effects, as described in Section 2.1.2.2

2.1.2.2 Long-term Effects

While studies have been conducted to compare the pre- and post- development hydrological conditions in the Klamath River basin (e.g. Hardy 1999, Hecht and Kamman 1996, USGS 1995 as cited by Hardy 1999), the results provide relatively little insight into the hydrological effects of the four Project dams because they also include the effects of the large-scale irrigation diversions and other infrastructure related to the BOR Klamath Project (Section 2.1.1). However, based on their limited active storage capacity, removal of the dams is not expected to greatly alter mean annual flows in the Klamath River. Small but significant impacts to summer low-flows on the middle Klamath River are possible, and discharge records upstream and downstream of the Project Reach may be useful for determining the likelihood of seasonal flow effects on downstream reaches if the four Project dams are removed. Additionally, as Iron Gate Dam is managed in part to re-regulate flows to the Klamath River, flow variability is likely to increase downstream of this dam should it be removed.

In the Project Reach, dam removal will significantly decrease the transit time of water in the Klamath River, since it will no longer be detained by the reservoirs. The total average theoretical hydraulic residence time (volume/flow) of the water impounded by the four Project reservoirs is approximately 27 days (Table 2), but ranges from about 10 days during high flows (i.e., 170 m^3/s [6,000 cfs]) to approximately 60 days during low flows (i.e., 28 m^3/s [1000 cfs]) (NRC 2004, FERC 2007). Dam removal would likely reduce the mean summer hydraulic residence time in the 38.2-mile Project Reach to several days, since travel times in the riverine stretch of longer length from Iron Gate Dam to Seiad Valley (61.6 river miles) are also estimated to be on the order of several days for typical flows (Deas and Orlob 1999).

2.1.3 Data Gaps

While the post-project hydrologic data record appears to be generally adequate to describe current Klamath River hydrology, direct isolation of the individual effects of the four Project dams is difficult because an extensive pre-project hydrologic data record is not available. This remains a data gap, which if addressed may also support an improved understanding of factors controlling hydrology of the Klamath River estuary during summer low-flow conditions (Section 3.1.3), As stated above, discharge records upstream and downstream of the Project Reach may be used to determine potential flow effects of dam removal on downstream reaches. Potential alterations to the operation of Keno Reservoir following removal of the four downstream Project dams should be included in an analysis of post-dam removal hydrology for the middle and lower Klamath River.

2.2 Water Temperature

2.2.1 Current Understanding

A wide variety of organizations have conducted water temperature monitoring in the Klamath River and its tributaries. For the purposes of this memorandum, we have considered efforts to synthesize this data rather than the raw data itself (Table 4).

Table 4. Water temperature data sources used for the analysis of dam removal effects on water quality.

Source[1]	Description of data	Dates available
Bartholow 2005	Water temperature trends in the Lower Klamath River, California	1962–2001
FERC 2007	Compilation of historical data from a variety of sources	2000-2004 and unspecified
PacifiCorp 2004a	Results of temperature modeling using compiled data from a variety of sources.	Unspecified
PacifiCorp 2005a	Compilation of historical data from a variety of sources	2000–2004

[1] Additional water temperature data has been collected by a broad range of organizations in the Klamath River and its tributaries. It is beyond the scope of this memorandum to catalog these results.

The entire Klamath River, as well as Upper Klamath Lake, Lost River, and the Klamath Straights Drain (which conveys water in both directions between Lower Klamath Lake and the Upper Klamath River) have been listed by California and Oregon as impaired for temperature under section 303(d) of the Clean Water Act (SWRCB 2006, ODEQ 2004). Water temperature in the Klamath River downstream of the Project Reach varies seasonally, with mean monthly temperatures in the river downstream of Iron Gate Dam ranging from 3–6 °C (37–43 °F) in January to 20–22.5 °C (68–72.5 °F) in July and August (Bartholow 2005). Longitudinal variations in temperature are less pronounced than seasonal variations. For example, between May 2001 and September 2002 the maximum difference in daily average water temperature between Link River downstream of Link Dam (RM 254.3) (upstream of Lake Euwana and the upper Klamath River) and the middle Klamath River downstream of Iron Gate Dam (RM 190.1) approached 8 °C (14 °F) in November 2002, but throughout the remaining months longitudinal temperature differences were less than 5 °C (9 °F) and in many cases were less than 2 °C (4 °F) (PacifiCorp 2004a).

Historically, summertime water temperature maxima in the Klamath River have been greater than other coastal rivers located to the north and south. For example, Blakey (1966) (as cited in Bartholow 2005) reports water temperatures in the Klamath River below the Trinity River confluence (RM 40.0) reaching 26.6 °C (79.9 °F) for up to 10 days per year, in contrast to proximal coastal rivers that never exceed this temperature. Bartholow (2005) presents evidence that a multi-decade trend of increasing water temperatures in the lower Klamath River is related to the cyclic Pacific Decadal Oscillation (PDO), and is consistent with a measured average basinwide air temperature increase of 0.33 °C /decade (0.59 °F/decade). The author estimates that the season of high temperatures that are potentially stressful to salmonids has lengthened by about 1 month since the early 1960s, and the average length of the lower river exhibits a summer water temperatures less than 15 °C (59 °F) has declined by about 8.2 km/decade (5.1 mi/decade). Further discussion of air temperature increases, as related to global climate change is presented in Section 1.

Although Bartholow's (2005) trend analysis of annual discharge to the lower Klamath River since the completion of Iron Gate Dam suggests that the observed water temperature increases in the lower Klamath River are not related to anthropogenic hydrological modifications, it does not preclude the possibility that the Project dams increase water temperatures over what they would be without dams. In particular, Iron Gate and Copco 1 dams may act to exacerbate water temperature warming trends in the river on a seasonal basis. Surface water warms in both Iron Gate and Copco 1 reservoirs thermally stratify beginning in April/May and do not mix again until October/November (FERC 2007). As powerhouse withdrawals are primarily from the epilimnion (surface waters), with withdrawal cones only periodically extending a short distance into the hypolimnion (Deas 2000, NRC 2004), temperature in waters leaving Copco and Iron Gate reservoirs reflect the warmer temperatures of surface water near 6-m (20 ft) and 12-meter (39 ft) depths, respectively (FERC 2007).

Temperature modeling scenarios (PacifiCorp 2005a) comparing the existing condition (all Project dams in place) to four without-project scenarios (i.e., no Project dams; without Iron Gate Dam; without Iron Gate, Copco 1 and 2 dams; and without Iron Gate, Copco 1 and 2, and J.C. Boyle dams) for 2001–2004 data indicate that the reservoirs act to generally cool release water from mid-January to April, variably cool or warm release water from April through early August, and warm release water from August through November. Just downstream of Iron Gate Dam, this translates to a 1–2.5 °C (1.8–4.5 °F) cooling during spring and a 2–10 °C (3.6–18 °F) warming during summer and fall (Figure 2-1). Immediately upstream of the confluence with the Scott River (RM 143.9), the difference between existing conditions and without-project scenarios indicates a lesser, albeit still measurable, warming of 2–5 °C (3.6–9 °F) for most of October and November, and at the confluence with the Salmon River (~RM 66) the temperature influence is mostly ameliorated (Figure 2-3). Since patterns in reservoir thermal structure for Iron Gate and Copco 1 indicate that stratification generally commences in April and ends in November, the effect of reservoir thermal regime on downstream water temperatures appears to be cooling during non-stratified periods and warming during stratified periods. Based on model results, the cooling effect in springtime, while potentially beneficial to rearing salmonids, seems to be of short duration and small magnitude. The warming effect, which can be stressful to rearing salmonids, lasts for the majority of summer and fall months and is of larger magnitude (PacifiCorp 2005a, QVIC 2006).

Reservoir thermal regimes also act to reduce the magnitude of diel temperature fluctuations in the reservoir reaches and the riverine reaches immediately downstream of Iron Gate Reservoir (Figure 2-1) (Deas and Orlob 1999, PacifiCorp 2005a). As with the seasonal temperature effect, the influence on diel temperature fluctuations is generally absent further downstream at the confluence with the Scott River (RM 143.9, Figure 2-2).

Additional water temperature modeling of existing conditions is currently underway as part of the TMDL process (NCRWQCB 2008). The TMDL water temperature model is built upon the PacifiCorp (2005a) model and includes updates and refinements which are expected to add to the general understanding of warming and cooling effects of the Project reservoirs on the middle and lower Klamath River.

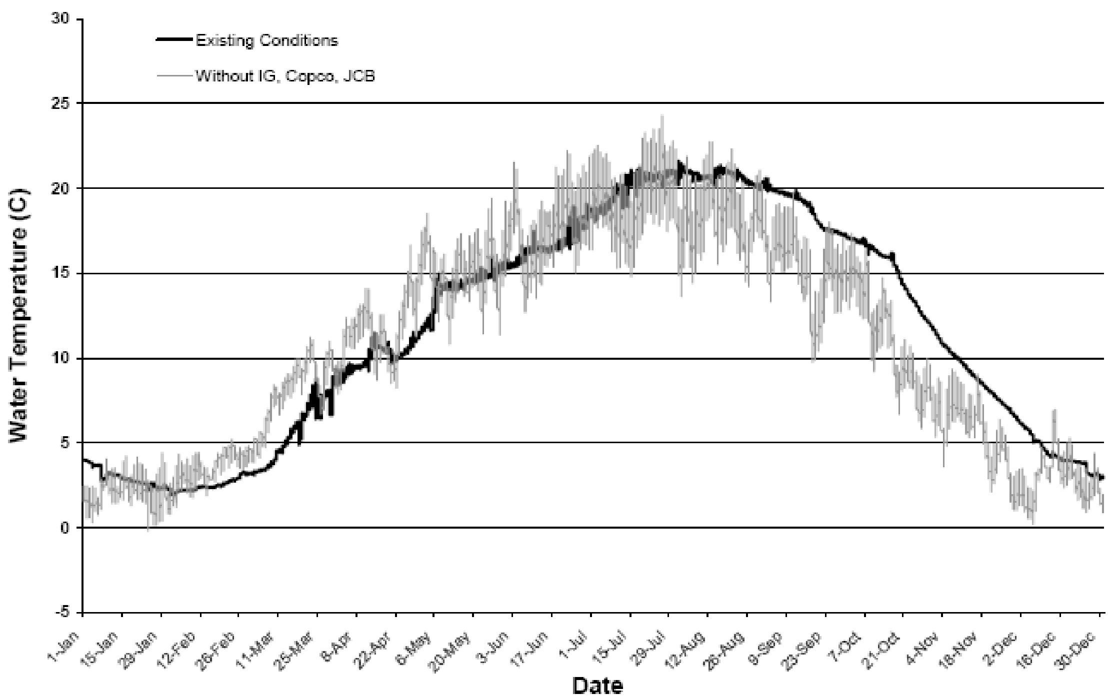

Figure 2-1. Simulated hourly water temperature downstream of Iron Gate Dam (RM 190.1) based on year 2004 for existing conditions compared to hypothetical conditions without Iron Gate (IG), Copco 1 and 2, and J.C. Boyle (JCB) dams. Source: PacifiCorp 2005a.

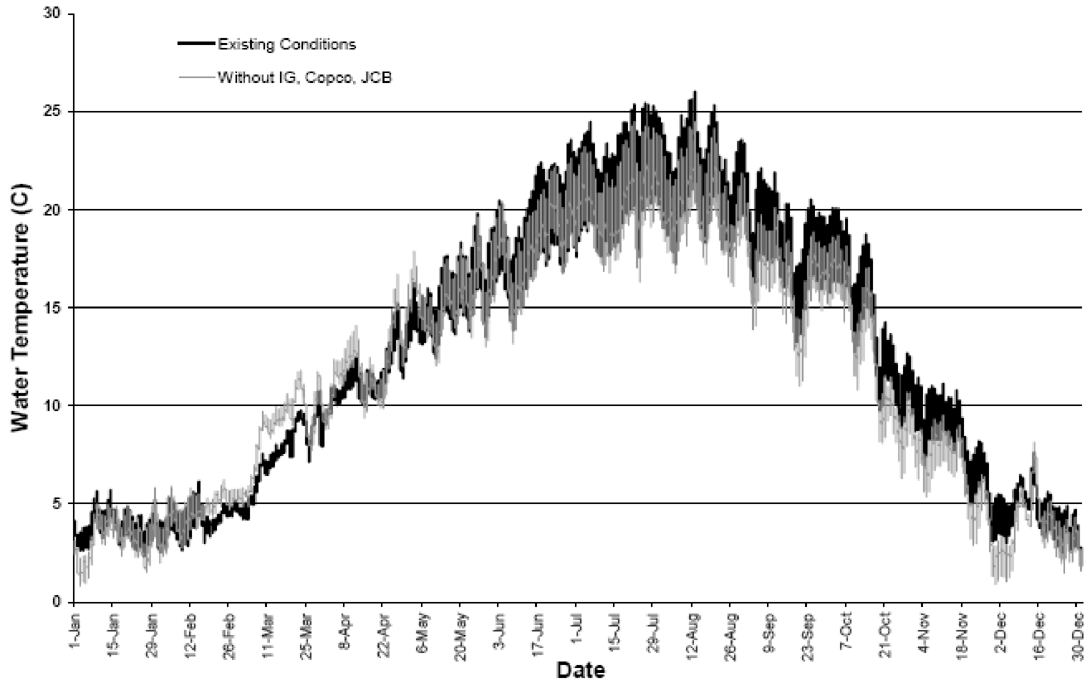

Figure 2-2. Simulated hourly water temperature immediately upstream of the Scott River confluence (RM 143.9) based on year 2004 for existing conditions compared to hypothetical conditions without Iron Gate (IG), Copco 1 and 2, and J.C. Boyle (JCB) dams. Source: PacifiCorp 2005a.

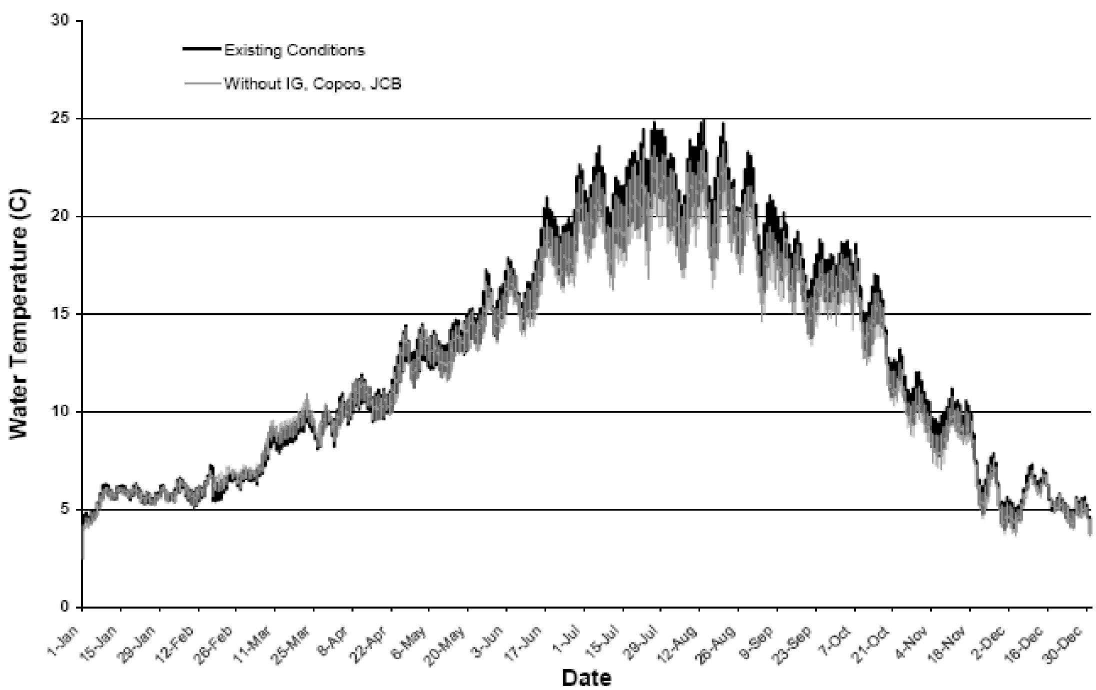

Figure 2-3. Simulated hourly water temperature downstream of the Salmon River confluence (RM 66) based on year 2004 for existing conditions compared to hypothetical conditions without Iron Gate (IG), Copco 1 and 2, and J.C. Boyle (JCB) dams. Source: PacifiCorp 2005a.

2.2.2 Anticipated Impacts of Dam Removal

2.2.2.1 Short-term Effects

Short term effects of dam removal on water temperature are not likely to differ substantially from long-term effects, described below.

2.2.2.2 Long-term Effects

Analyses of existing water temperature data for the Klamath River indicate the following: 1) maximum temperatures in the lower Klamath River are higher than those of other nearby coastal rivers (Blakey 1966 as cited in Bartholow 2005), 2) temperatures have increased along with measured average basinwide air temperatures over the period 1962–2001 (Bartholow 2005), and 3) on a seasonal basis, Iron Gate and Copco 1 Reservoirs appear to decrease spring temperatures and increase summer and fall temperatures in the middle Klamath River; the latter potentially exacerbates basin-scale warming trends in this reach. Based upon these results, and in the absence of warming caused by potential climate change effects (see Section 2.7), removal of the Project dams is expected to cause a water temperature decrease in middle Klamath River during summer and fall, with the greatest cooling likely to occur just downstream of Iron Gate Dam. Modeling results from with- and without-project scenarios (PacifiCorp 2005a) suggest that the decrease could amount to a maximum of 10 °C (18 °F) during summer and fall, exhibited just downstream of Iron Gate Dam (RM 190.1). Immediately upstream of the confluence with the Scott River (RM 143.9), the difference between existing conditions and the without-project scenarios indicates the potential for a maximum of 5° C (9 °F) cooling during late fall (i.e., October and November).

Localized areas of cooler water, such as those occurring at the mouths of tributaries, have been shown to be used as thermal refugia by salmonids (Yurok Tribal Fisheries Program 2003 and 2005). Since removal of the Project dams is not expected to dramatically alter hydrology and geomorphology of the lower Klamath River, the temperature and extent of such refugia are not likely to be impacted. However, the potential for this effect has not been specifically investigated.

The dams also act to reduce the magnitude of diel temperature fluctuations in the reservoir reaches and the riverine reaches immediately downstream of the reservoirs (Deas and Orlob 1999). It is not clear how this modified diel cycle might affect water resources.

2.2.3 Data Gaps

Water temperature data for the Klamath River Basin is extensive, and the temperature dynamics of the river are generally considered to be well-captured by the PacifiCorp/Tetra Tech models (PacifiCorp 2005a, Asarian and Kann 2006b, Tetra Tech *in prep*). Although presently there are no clearly identifiable data gaps with regard to Klamath River water temperature and dam removal, continued monitoring of water temperature will be critical for assessing the effects of dam removal, particularly within the context of ongoing climate change.

2.3 Sediment and Turbidity

2.3.1 Current Understanding

The lower Klamath River downstream of Trinity River confluence (RM 40.0) is listed as sediment impaired under Section 303(d) of the Clean Water Act (SWRCB 2006). A common water quality indicator for sediment impairment is increased turbidity and total suspended solids (TSS) levels. As shown in Table 5, turbidity data at multiple sites in the Klamath River has been collected from January 1980 through December 2003, including sites upstream, within, and downstream of the Project Reach.

Table 5. Sediment and turbidity data sources used for the analysis of dam removal effects on Klamath River water quality.

Source	Description of data	Dates available
Eilers and Gubala 2003	Bathymetric data and sediment analysis in Keno, J. C. Boyle, Copco 1 and Iron Gate Reservoirs.	2002
Eilers and Raymond 2005	Sediment oxygen demand from six sediment samples collected throughout the basin	2004
GEC 2006	Study of sediment volume and size in J. C. Boyle, Copco 1 and Iron Gate Reservoirs. Also included screening for contaminants.	2006
PacifiCorp 2004b	Monthly turbidity, flow, chlorophyll-a for the middle Klamath River compiled from historical sources (1980–2001) and new data (2001–2003)	1980–2003
YTEP 2005	Winter turbidity and TSS data in three tributaries (McGarvey Creek, Blue Creek, and Turwar Creek) downstream of the Trinity River (RM 40.0).	2003–2004

Although not all sites were consistently monitored throughout the historical record, in general the available data indicates that turbidity decreases longitudinally from upstream to downstream between Link River at Klamath Falls (RM 253.1) and Orleans (~RM 59). Seasonal variation in turbidity is evident, with peak values occurring primarily during summer months but occasionally corresponding to wintertime high flow events (PacifiCorp 2004b). Single-factor correlations of the 1980–2003 dataset using separate linear regressions of turbidity (NTU) versus mean monthly flow (cfs) and turbidity (NTU) versus chlorophyll-*a* (chl-*a*) (ug/L) at several sites indicate high variability for both the turbidity regression with flow (maximum r^2<0.35) and chl-*a* (r^2=0.24) (PacifiCorp 2004b). These results indicate that neither flow nor algal growth was singularly sufficient to describe the observed variations in turbidity. TSS in the data record is more limited, but levels from 2001–2003 also exhibit overall longitudinal decreases in concentration with consistently low TSS (<8 mg/L) measured below Iron Gate Dam (PacifiCorp 2004b).

Despite the lack of strong correlation between chl-*a* and turbidity in the long-term data record (PacifiCorp 2004b), more comprehensive data from 2003, including chl-a, TSS and turbidity, indicate that high concentrations of algae (specifically cyanobacteria) downstream of Link River at Klamath Falls (RM 253.1) are responsible for creating elevated TSS and turbidity levels upstream of the Project Reach during summer months (PacifiCorp 2004b). This is not surprising as algal growth in eutrophic and mesotrophic water bodies is known to result in significant increases in turbidity and TSS levels (Horne and Goldman 1994). As shown in Figure 2-4, samples collected from downstream of Link Dam during July, August, and September 2003 exhibit algal concentrations greater than 20 mm^3/L, minimum turbidity of 15 NTU, and minimum TSS of 15 mg/L (Kann and Asarian 2006, PacifiCorp 2004b). Earlier and later in the summer of 2003, lower phytoplankton levels correspond to lower turbidity and TSS levels in the river upstream of J.C. Boyle Dam (RM 224.7). Additionally, although there is an overall trend of decreasing TSS from upstream to downstream of the Project dams, relative increases in TSS observed in Copco 1 and Iron Gate dam outflows during mid-August and mid-September of

2003, respectively, correspond roughly to increases in chl-a concentrations (ug/L) at the same locations (PacifiCorp 2004b).

Seasonal variations in the relationship between turbidity and TSS can also provide information about the composition of suspended sediments in the Klamath River. While a relationship between TSS and turbidity was not presented in PacifiCorp (2004b), a regression analysis of the 2003 data can be used to investigate the relative contribution of mineral- versus algal-derived sources of suspended sediment in the Klamath River from Link River at Klamath Falls (RM 253.1) to Iron Gate Reservoir (RM 190.1). Numerous previous studies have indicated log-linear or linear relationships (approximating 1:1) between TSS concentration and turbidity in rivers (Clifford et al. 1995, Davies-Colley and Close 1990, Gippel 1988, Gippel 1995, Malcom 1985, Pfannkuche and Schmidt 2003, Wass and Leeks 1999), due to the fact that the light scattering coefficient measured at a 90° angle in turbidity instrumentation behaves almost proportionally to the suspended particle concentration (van de Hulst 1957). Despite this, for the same TSS concentration and particle size, algal-derived sources have been shown to produce proportionally higher turbidity values than mineral particles, suggesting that during periods of high suspended algal growth and transport, the TSS and turbidity relationship may be significantly less than 1:1 (mg/L per NTU). In addition, light absorption by natural organic matter has been shown to increase turbidity readings by as much as 10% (Gippel 1995, Malcolm 1985), which may also result in seasonal relative differences between the two parameters.

As shown in Figure 2-4 and, Figure 2-5 the relationship between TSS and turbidity for the 2003 Klamath River samples was 1:1 during April through November 2003 and across all sites (r^2=0.83, p<0.0001 excluding one outlier). The regression closeness of fit and the 1:1 correspondence across all of the data suggest that distribution of the transported grain sizes in the Klamath River upstream of Iron Gate Dam was comparatively homogeneous from spring through early winter. A slight seasonal variation signal may be present in the dataset. As shown in Figure 2-4, a slightly lower regression slope (m=0.91) was observed during summer/fall (July – October), as compared with the overall April – November dataset (m=1.00). While this may suggest a relatively greater contribution by low-mineral content (e.g., organic) particles such as algae or other natural organic matter (NOM) during summer and fall, within the uncertainty of the analysis a seasonal signal is not particularly evident. The July – October 2003 TSS and turbidity record did coincide with a large algal bloom in the upper Klamath River near Link Dam (RM 254.3) (Asarian and Kann 2006b) (Section 2.6).

Table 6. Regression analysis for TSS and turbidity, April through November 2003 (data from PacifiCorp 2004b).

Sample months	Linear regression coefficients TSS (mg/L) = m*(Turbidity [NTU])+b			
	m	**b**	**R^2**	**p**
Mainstem (April – November)	1.0012	-1.1403	0.83	<0.0001
Mainstem (July – October)	0.9096	-0.3326	0.81	<0.0001
Tributaries (December – February)	3.8371	-2.9001	0.89	<0.0001

No coincident TSS and turbidity data are available for winter months in the Klamath River either upstream or downstream of Iron Gate Dam. However, December through February 2003 TSS and turbidity data for Blue Creek, McGarvey Creek, and Turwar Creek, located immediately upstream or within a few river miles upstream of the Klamath River estuary, exhibit a slope almost four times greater than that of summertime data in the Klamath River, indicating correspondingly higher relative mineral input. At 176 NTU, peak wintertime turbidity from the tributaries is greater than peak summertime turbidity (23 NTU) in the mainstem during the same year. This is also the case in the historical record (PacifiCorp 2004b). Slightly greater overall variability in the 2003 wintertime TSS and turbidity data for the tributaries is reflected by the relatively wider 95% confidence bands in Figure 2-5.

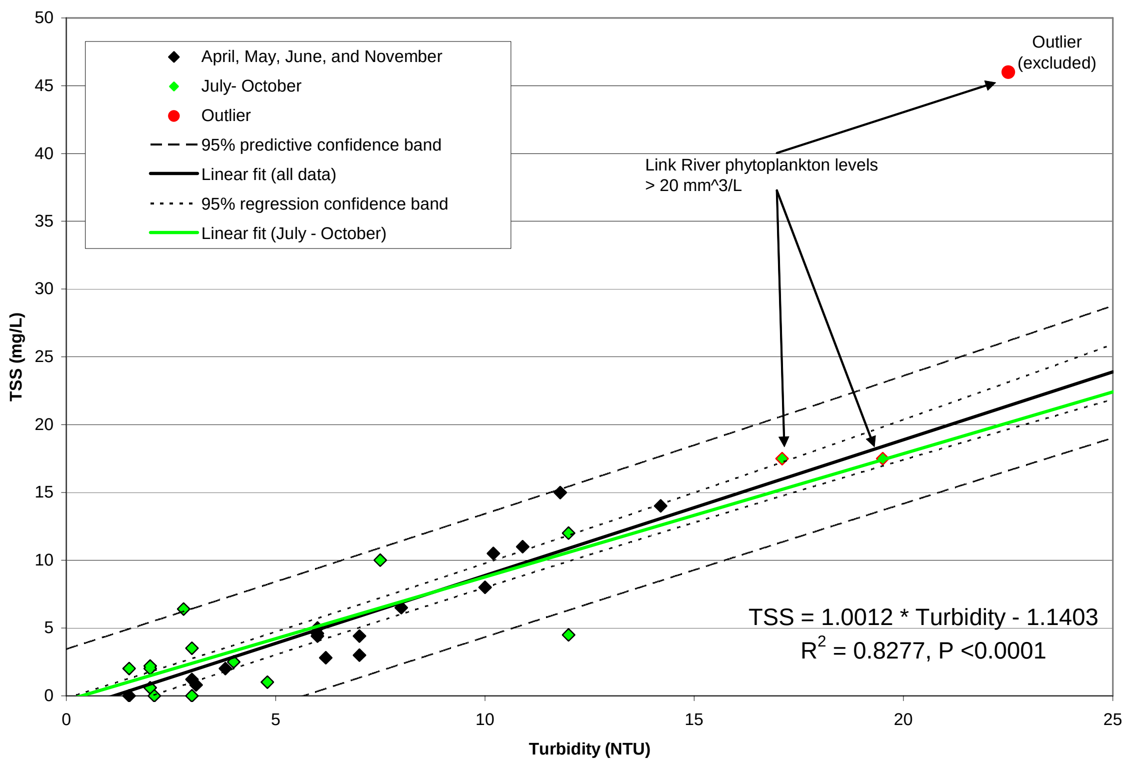

Figure 2-4. Relationship between total suspended solids (TSS) and turbidity in the Klamath River, April through November 2003.

The available data suggest that wintertime TSS and turbidity are generally associated with mineral sources transported during storm events. In contrast, summertime TSS and turbidity in the Klamath River from Link River to Iron Gate Dam appear to be dominated by algal-derived TSS, a significant portion of which originates from Upper Klamath Lake, flows into the Klamath River, and is intercepted by the dams. While PacifiCorp (2004b) attributes seasonal turbidity reductions to spring accretion flows between the J.C. Boyle dam and powerhouse in the bypass reach downstream of J.C. Boyle dam, sediment and algal interception and retention by the dams appears to be predominantly responsible for the relatively low TSS and turbidity levels available for transport further downstream to the lower Klamath River.

Indeed, data collected to date indicate that 11.1 million m^3 (Eilers and Gubala 2003) to 15.6 million m^3 (GEC 2006) (14.5 to 20.4 million yd^3) of sediment deposits are stored within the four Klamath River reservoirs. Sediment texture analysis results of the current reservoir deposits indicate that the deposits are comprised of predominantly fine material (e.g., silt and clay <0.0625 mm [GEC 2006]), and a relatively large fraction by volume of the accumulated material is organic carbon (i.e., 3% to 5%). Organic carbon in reservoir sediments typically ranges 0.3% to 5.6% (mean of 1.9%) by volume of total sediment deposits (Ritchie 1989). Additionally, approximately 30% by volume of the organic carbon is expected to be released given model runs for normal water year conditions on the Klamath River (Stillwater Sciences 2008). While a large portion of the organic material is presumably due to detrital algal biomass transported into the Project Reach from the Upper Klamath River, a significant fraction may be a result of algal growth occurring within the reservoirs themselves. As a conservative estimate, discounting 5% of the existing sediment deposits from the total volume due to assumed reservoir-associated algal productivity and assuming fine sediment deposition in a riverine environment would be negligible over a time scale of approximately 50 years, rough calculations indicate that an average of 0.2 to 0.3 million m^3/yr (0.3 to 0.4 million yd^3/yr) of mineral sediment would have been transported downstream in the absence the dams. These are average estimates only and it is expected that inter-annual sediment and algal loads would vary with precipitation, meteorology, and reservoir mixing conditions affecting algal growth dynamics.

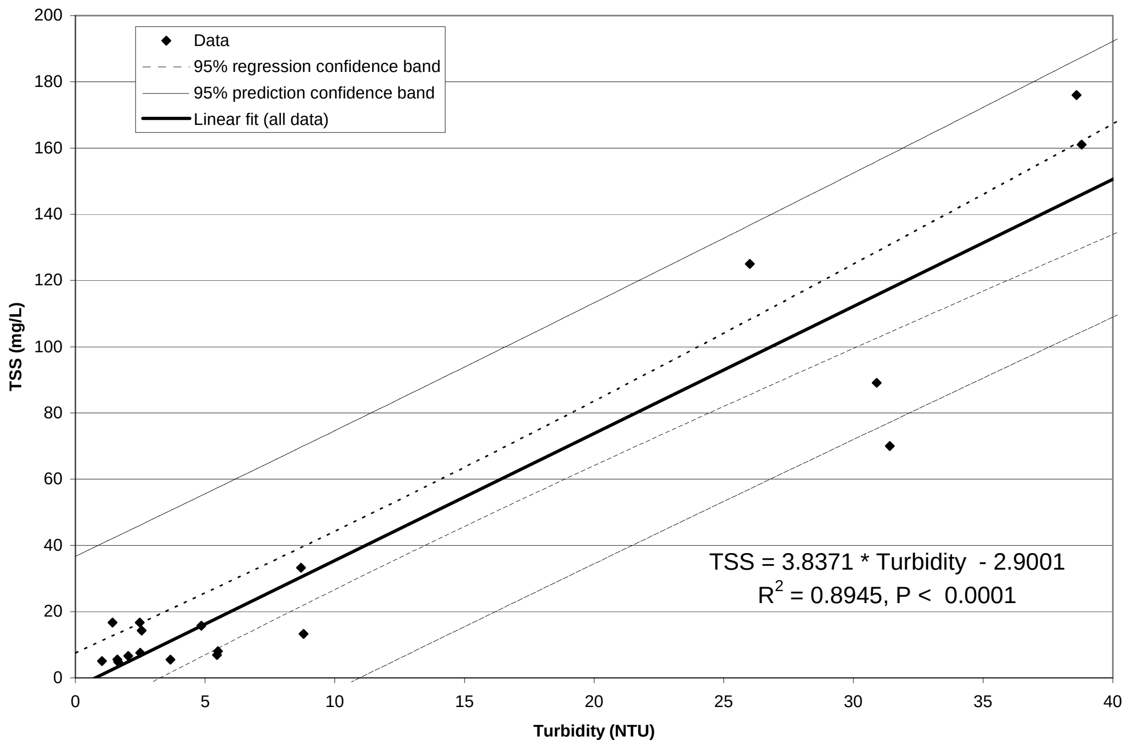

Figure 2-5. Relationship between total suspended solids (TSS) and turbidity for lower Klamath River tributaries McGarvey, Turwar, and Blue Creeks during winter 2003–2004.

2.3.2 Anticipated Effects of Dam Removal on Sediment and Turbidity

2.3.2.1 Short-term Effects

Sediment transport modeling of the impacts of dam removal on TSS and turbidity in the lower Klamath River indicates high short-term (1–2 years) suspended sediment loads downstream of the Project dams (Stillwater Science 2008a). The preferred drawdown scenario begins in early November to ensure that maximum suspended sediment concentrations will occur during winter months when flows are naturally high in the mainstem river, however in spring (after March 21) predicted sediment concentrations may still be relatively high (300–500 mg/L TSS) downstream of Orleans (~RM 59) (Stillwater Sciences 2008).

In addition to the short-term release of organic carbon (approximately 230,000 metric tons [Stillwater 2008a]) contained within the reservoir deposits (see Section 2.4.2 for discussion of potential impacts due to organic carbon transport), sediment-associated contaminants will be transported through the Klamath River following dam removal and could result in short-term adverse effects on biota exposed to high suspended sediment loads. To investigate the potential for sediment toxicity, Shannon and Wilson (2006) collected 26 cores from J. C. Boyle, Copco 1, and Iron Gate reservoir deposits, and analyzed them for contaminants including acid volatile sulfides, metals, pesticides, chlorinated acid herbicides, polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), cyanide, and dioxins. No herbicides or PCBs were found and only one sample exceeded Puget Sound Dredge Disposal Analysis (PSDDA) screening levels for ethyl benzenes and total xylenes, which are volatile compounds and will partition into the air upon release from the reservoir (Shannon and Wilson 2006). Although there is not a sediment quality standard or guideline for dioxin, sediment levels measured did not exceed PSDDA screening levels reported by Shannon and Wilson (2006) and a more comprehensive review of dioxin guidelines and sediment studies from watersheds outside of the Klamath basin conducted by Dillon (2008) indicated that measured sediment levels of dioxin are not expected to adversely effect fishery resources during dam removal. While cyanide was detected in multiple sediment cores, it was not found in toxic free cyanide form (HCN or CN^-), and is not likely bioavailable.

2.3.2.2 Long-term Effects

Based on the available information, it is expected that long-term wintertime TSS and turbidity associated with mineral sources will increase in the lower Klamath River if the dams are removed, and peak levels will be associated with high-flow events. Peak wintertime TSS and turbidity levels are expected to be greater than 50 NTU and 150 mg/L TSS, based on the combination of historical high-flow turbidity data and the 2003 relationship between TSS and turbidity (Figure 2-4, Table 6), however these are rough estimates derived from limited available data.

The effects of dam removal on long-term TSS and turbidity levels during the growth season are less certain. As described above, both data (PacifiCorp 2004b, Asarian and Kann 2006a) and modeling (PacifiCorp 2005a) show that summertime turbidity levels decrease from upstream to downstream throughout the Project Reach. The relatively large fraction of organic material accumulated in the reservoir sediments (i.e., 766,000 metric tons, of which approximately 30% is expected to be released following dam removal) corroborates data interpretation that upstream and in-reservoir algal growth is largely intercepted and retained in reservoir sediments. However, as noted above, there are exceptions in the historical and more recent 2003 datasets when turbidity increases downstream of the dams during summer months i.e., relative increases in TSS in Copco 1 and Iron Gate dam outflows during mid-August and mid-September 2003 and general correspondence to increases in chl-a at the same locations (PacifiCorp 2004b). These episodic increases in TSS and turbidity resulting from in-reservoir algal productivity are not expected to occur following dam removal; however, continued transport of algal-dominated TSS and turbidity from Upper Klamath Lake (RM 254.3) will likely increase levels of these constituents in the lower Klamath River during the growth season.

2.3.3 Data Gaps

Partial deposition of algal-derived TSS (i.e., from phytoplankton) and turbidity transported to the Klamath River from Upper Klamath Lake may still occur in the absence of the Project dams. DREAM-1 modeling of fine sediment transport following potential dam removal indicates that sediments currently stored behind the dams will not deposit in the river, assuming a drawdown scenario beginning in November (Stillwater Sciences 2008). Algal-derived TSS, which predominates during summer months, is also likely to remain suspended based on the typical range of settling velocities for phytoplankton (0.05-15 m/d [Bowie et al. 1985]) compared with the highly advective environment of the Klamath River where current velocities exceed 0.3 m/s. A more thorough analysis of existing data (e.g., TSS, turbidity, and algal concentrations in the Klamath River downstream of Iron Gate Dam) will support better characterization of the no-dam scenario with regard to summertime conditions when algal-derived TSS is predominant. This could include analysis of existing phytoplankton concentrations in the lower Klamath River (2005–2007 [YTEP 2005, 2006, 2007, 2008a]) to determine whether any fractions of the phytoplankton are currently settling out in lower velocity reaches of the river or backwaters, or if they are predominantly transported directly to the Pacific Ocean.

2.4 Nutrients

2.4.1 Current Understanding

Currently, the entire Klamath River and its tributaries are listed as impaired under section 303(d) of the Clean Water Act for nutrients and dissolved oxygen (SWRCB 2006, USEPA 2006). High levels of nitrogen and phosphorus in lakes and rivers have the potential to impact overall water quality by increasing rates of algal growth and decay, which can lead to increased levels of turbidity, large fluctuations in dissolved oxygen and pH levels, as well as potential increases of toxic substances such as ammonia (NH_4^+/NH_3), hydrogen sulfide (H_2S), and release of heavy metals from low oxidation-reduction potential at the sediment water interface.

Several studies have been undertaken to examine nutrient levels in the Klamath River (Table 7). An analysis of three consecutive years of nutrient speciation data upstream, within, and downstream of the Project reservoirs is being conducted, however results will not be released until 2009 (Kann and Asarian *in prep*) Thus, this water quality technical report relies upon data gathered by PacifiCorp, USFWS, CDFG, and the Yurok and Karuk Tribes during the past 12 years. Studies listed in Table 7 examine total nitrogen (TN), total phosphorous (TP) and in many cases include nutrient speciation such as nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+), total Khjedahl nitrogen (TKN), ortho-phosphorus (ortho-P, often measured as soluble reactive phosphorus), as well as chl-*a* and total organic carbon (TOC).

Table 7. Nutrient information sources used to support the analysis of dam removal effects on water quality.

Source	Description of data	Years available
Asarian and Kann. 2006a	Presentation of TN data from TMDL database, including entire Klamath River mainstem and tributaries.	1996–2004
Asarian and Kann 2006b	Presentation of TN, TP, TOC, and chl-*a* data from TMDL database, including entire Klamath River mainstem and tributaries. Also includes presentation of 2001 N and P species.	2000–2004
Hoilman et al. 2008	Weekly summer chl-*a*, N and P species from Upper Klamath Lake.	2005
Kann and Asarian 2005	TN, TP and N species loading in Iron Gate and Copco 1 Reservoirs used in an analysis of seasonal reservoir retention	2002
Kann and Asarian 2007	Bi-weekly summer chl-*a*, pheophytin, N and P species in Iron Gate and Copco 1 reservoirs, and in nearby Klamath River mainstem and tributaries.	2005–2006
USFWS 2004a	Fall TOC, chl-*a*, pheophytin, N and P species sampled in Iron Gate Reservoir at a range of depths, as well as sites upstream and downstream of the reservoir to assess conditions at fall turnover.	2004
USFWS 2004b	August chl-*a*, pheophytin, N and P species sampled in Iron Gate Reservoir and sites downstream to Orleans (~RM 59) to assess water quality under pulse flow conditions.	2004
USFWS 2008b	Database of Klamath River mainstem and tributary nutrient data including N and P species, chl-*a*, and a variety of other water quality constituents.	2001–2005
Wood et al. 2006	Weekly summer chl-*a*, N and P species from Upper Klamath Lake	2002–2004
YTEP 2005, 2008b	Summer TOC, chl-*a*, pheophytin, N and P species from Trinity River confluence (RM 40.0) to the estuary (RM 4).	2004, 2007

2.4.1.1 Seasonal and longitudinal nutrient patterns

Total nitrogen and phosphorus

Water entering the Project reservoirs from the upper Klamath River in the spring, summer, and fall is relatively high in nutrients, with TN during 2001–2004 of approximately 1.7 mg/L (sum calculated from mean values of TKN, NO3, and NH3 as given in Table 6 [PacifiCorp 2005a]) and mean TP of 0.22 mg/L downstream of Keno Dam (RM 228.2) (PacifiCorp 2005a). Of TN, a mean of 0.50 mg/L-N is present as NO_3^- and 0.13 mg/L-N is present as NH_4^+ (2001–2004 dataset). A significant portion of TP entering the Project reservoirs is present as ortho-P, with 2001–2004 levels averaging 0.14 mg/L (PacifiCorp 2005a).

Nutrient concentrations generally decrease with distance downstream of J. C. Boyle Dam (RM 224.7). For example, nutrient concentrations in the middle Klamath River downstream of Iron Gate Dam (RM 190.1) average approximately 1.2 mg/L TN and 0.17 mg/L TP (PacifiCorp 2005a) while in the lower Klamath River downstream of the Trinity River confluence (RM 40.0), TN and TP are typically less than 0.5 mg/L and less than 0.1 mg/L, respectively (YTEP 2005 and 2008b). While dilution of nutrient concentrations by less nutrient-rich waters within the Project Reach has been shown to occur (PacifiCorp 2005a), data and early modeling studies concluded that the Project reservoirs act primarily as TN sinks due to trapping of algal detritus (particularly the larger and deeper Copco 1 and Iron Gate) when viewed on an annual basis in 2000–2004 (PacifiCorp 2004a, 2005b, 2005c; FERC 2007). Interception and retention of algal-associated TSS and turbidity over time by the four Project dams is evident (Section 2.3), and this includes nitrogen and phosphorus contained in algal biomass.

Despite the indication that TN and TP are removed from the Project Reach through reservoir-induced settling, the validity of the PacifiCorp annual nutrient sink assertion has been questioned, because the reservoirs also periodically increase loading of TN and TP by transfer of sediment-associated nutrients to the water column, and possibly through direct nitrogen fixation from the atmosphere by cyanobacteria (i.e., blue-green algae) (Asarian and Kann 2006b, Butcher2008). For example, in 2002 TP and TN were released from Copco 1 and Iron Gate Reservoirs immediately preceding and during reservoir blooms of *Aphanizomenon flos-aquae* (Kann 2006, Kann and Asarian 2006). Re-analysis of the 2002 dataset for Iron Gate and Copco 1 Reservoirs indicated that while there may be a small net retention of TP and TN in the Project reservoirs on an annual basis, significant periods of nutrient release also occur during critical spring and summer periods when nutrients can stimulate primary productivity in downstream riverine reaches (Kann and Asarian 2005). Subsequent analyses undertaken by Kann and Asarian (2006) showed that the PacifiCorp nutrient model tended to under-predict TN concentrations in the Klamath River and both over- and under-predicted TP, depending on river mile, due to inadequacies in the nutrient dynamic model components. Finally, in a later analysis of differing approaches and results to determining nutrient budgets in the Klamath River, Butcher (2008) found that estimates of nutrient retention in the Project reservoirs were in general agreement given the uncertainties and sparse availability of data, and that nutrient removal from the system (as opposed to retention) due to denitrification of nitrogen and deposition of insoluble forms of phosphorus is less than 1% of TN and TP loads in the Project reservoirs.

Overall then, the Project reservoirs appear to be acting as TN and TP sinks on an annual basis but as either sources or sinks on a seasonal basis. The intrinsically high rates of phytoplankton growth and/or decay in the reservoirs cause seasonal anoxic hypolimnetic conditions and high pH, which then have the potential to alter both the short-term loading and form (i.e., NO_3^-, NH_4^+, TKN, ortho-P [mg/L]) of nutrients to the middle and lower Klamath River (Asarian and Kann 2006a–b; Kann and Asarian 2005, 2006 and 2007; Tetra Tech *in prep*.). Periods of nutrient release from the reservoirs have been shown to make nitrogen and phosphorus available to downstream reaches on a seasonal basis (Kann and Asarian 2007, Kann and Asarian 2006) and total nutrient removal from the system on an annual basis at present appears to be very low (Butcher 2008). The following sections summarize dynamics for NO_3^-, NH_4^+, TKN, ortho-P.

Nitrate

In summer 2001, NO_3^- concentrations increased approximately 0.5 mg/L from the outflow of Link Dam to the outflow of Iron Gate Dam, and in summer 2002, an increase of 0.5 mg/L in NO_3^- concentrations was observed also between inflow and outflow of Copco 1 Dam, with little increase occurring in Iron Gate Dam. However, data from summer and fall of 2005 shows overall decrease of approximately 0.5 mg/L NO_3^- in Copco 1 and Iron Gate Reservoirs. Seasonal data indicates that NO_3^- levels tend to decrease during phytoplankton blooms: in particular, fall cyanobacteria blooms were recorded in Iron Gate and Copco 1 reservoirs in summer and fall 2005 coincident with the decrease in NO_3^- concentrations.

Ammonium

Elevated ammonium levels can be harmful to aquatic life. Ammonia toxicity to fish is temperature and pH dependent, with acute exposure resulting in potential mortality and prolonged exposure to sub-lethal levels potentially leading to skin and gill hyperplasia, respiratory problems, stress, and conditions which support proliferation of opportunistic bacteria and parasites. High pH levels also measured in the Klamath River downstream of Iron Gate Dam from June through October (Section 2.5) can cause conversion of NH_4^+ to the toxic unionized form (NH_3). While periods of elevated (>0.5 mg/L) NH_4^+ levels have occurred at least once per year from 2002–2005 in Upper Klamath Lake (Wood et al. 2006, Hoilman et al. 2008), within the Project Reach NH_4^+ levels are generally relatively low, with only minor increases (0.05–0.1 mg/L) observed to occur between the inflow and outflow of Copco 1 and Iron Gate Reservoirs (Kann and Asarian 2005, 2007). A mean of 0.13 mg/L NH_4^+ for 2000–2004 data from the Iron Gate Dam outflow has been reported (PacifiCorp 2005a). The NCRWQCB recently evaluated all available sampling data records as part of their Klamath River TMDL development. Sampling events in which all three parameters (pH, NH_4^+, and temperature) were collected simultaneously indicated no documented acute or chronic toxicity exceedances for ammonia (NCRWQCB 2008).

While available data collected to date suggests no ammonia toxicity associated with the operation of Project dams, elevated NH_4^+ levels in the deeper portions of the hypolimnion of Iron Gate and Copco 1 reservoirs in summer of 2005 (exceeding 0.6 mg/L in both reservoirs [Figures 12 and 14 in Kann and Asarian 2007]) indicate that anoxic conditions are likely causing conversion of organic nitrogen in reservoir deposits to ammonia, which introduces the potential for episodic toxicity events depending upon reservoir mixing conditions.

Ortho-phosphorus

During summer 2001, there were increases of roughly 0.05 to 0.1 mg/L in ortho-P concentrations between the outflow of Link Dam (RM 253.9) and the outflow of Iron Gate Dam (RM 190.1). In summer 2002 both Iron Gate and Copco 1 reservoirs showed slight net retention of ortho-P early in the summer (~0.02 mg/L in Copco 1, ~0.04 mg/L in Iron Gate), but showed variable retention rates for the remainder of the year. In 2005, Copco 1 and Iron Gate reservoirs showed net retention (~0.05 mg/L in each reservoir) in the summer, but Copco 1 Reservoir showed little net retention or loading in the fall, while Iron Gate Reservoir released ortho-P (~ 0.025 mg/L) in the fall. As with NO_3^-, high (> 0.2 mg/L) ortho-P levels were measured in the deeper portions of the hypolimnion of Iron Gate and Copco 1 reservoirs in fall 2005.

2.4.1.2 Current nutrient impacts to water quality

Although the NCRWQCB Basin Plan includes a 10 mg/L NO_3^- as N (45 mg/L as NO_3^-) criterion for municipal water supply (NCRWQCB 2006a), no numeric nutrient criteria are listed for the California portion of the Klamath River. In Oregon, the ODEQ also does not list numeric nutrient criteria, but does include criteria to protect aquatic life from ammonia toxicity as a function of pH and temperature (OAR 2008, USEPA 1999). In 2006, Kier Associates (2006) assisted the Hoopa Valley Tribe in developing numeric nutrient criteria for TN and TP in the middle and lower Klamath River based on an analysis of theoretical nutrient limitation for algal growth (Hoopa Valley Tribe 2008). Using the Redfield ratio of nitrogen to phosphorus found in algae (7.2:1) (Smith et al. 1997), Kier Associates (2006) examined limiting nutrient concentrations in the Klamath River on the basis of total concentrations (TN:TP) as well as the more bioavailable dissolved inorganic concentrations (TIN:ortho-P). The nutrient limitation analysis indicated that the Klamath River is generally nitrogen limited, as found in other studies

(PacifiCorp 2004a, Tetra Tech 2004 as cited in Hoopa Valley Tribe 2008), but the analysis also found occasional phosphorus limitation or co-limitation (Hoopa Valley Tribe 2008). The Hoopa Valley Tribe nutrient criteria analysis also included comparisons to estimated background concentrations for the Klamath Mountains sub-ecoregion (USEPA 2000a). Nutrient levels in the relatively higher quality Trinity River were also mentioned in the analysis but not explicitly presented (Hoopa Valley Tribe 2008). The resulting recommended nutrient criteria are 0.2 mg/L TN and 0.035 mg/L TP, which represent mean concentrations measured in any 30-day period from May through October. Nutrient levels below these criteria are not expected to negatively impact the middle and lower Klamath River. Although the Hoopa Valley Tribe (2008) TN and TP criteria may be altered through adjustment of the definition of natural conditions by the ongoing TMDL process, they currently represent the only benchmark for nutrient-related water quality impairment on the Klamath River.

On an annual basis, 2001–2004 median nutrient concentrations in the upper and middle Klamath River consistently exceeded the Hoopa Valley Tribe criteria from Link Dam (RM 253.9) to Seiad Valley (RM 129.4). Downstream of Seiad Valley, median TN and TP concentrations were often at or only slightly greater than Hoopa Valley nutrient criteria (Asarian and Kann 2006b). Given the Klamath River's historically mesotrophic status, and the necessity for a dataset large enough to account for the observed high inter-annual and spatial variability in water quality constituents, it has been difficult to demonstrate clear impacts to the river based on elevated nutrient concentrations. Using summer 2004 data, Kier Associates (2006) found significant relationships between maximum summer periphyton biomass (measured as chl-*a* mg/m^2) and mean summer daily maximum pH ($p=0.0030$, $r^2=0.89$), mean summer daily pH range ($p=0.0079$, $r^2=0.91$), and mean summer daily dissolved oxygen range ($p=0.0046$, $r^2=0.94$). However, there were no discernable relationships between maximum summer periphyton biomass and nutrient concentrations in the middle and lower Klamath River, including TP, TN, and various nitrogen and phosphorus species (Kier Associates 2006). On one documented occasion, in September 2007, a significant spike in nutrient concentrations for TN and TP, soluble reactive phosphorus (SRP), and TOC was documented in the lower river downstream of the Trinity River confluence (RM 40.0) (YTEP 2008b). Nutrient levels increased to 0.5 mg/L TN, 0.1 mg/L TP, and 2.5 mg/L TOC, with simultaneous increases in chl-*a*, pheophytin-a, phytoplankton density, and density of the toxin-producing cyanobacteria *Microcystis aeruginosa.* Note that the September 2007 *Microcystis aeruginosa* bloom extended from Iron Gate Dam (RM 190.1) to the mouth of the Klamath River (RM 0.0) (Section 2.6.1.1), but nutrient concentrations were only available downstream of the Trinity River confluence (RM 40.0)

2.4.2 Anticipated Impacts of Dam Removal

2.4.2.1 Short-term Effects

Current dam removal scenarios indicate increased suspended sediment loads to the middle and lower Klamath River 1–2 years following dam removal (Section 2.3.2.1). The increase in TSS is also expected to increase short-term TN and TP concentrations in the middle and lower Klamath River because particulate and organic nutrients contained in reservoir sediment deposits will be transported along with the sediments themselves. Estimated release of organic carbon (including TN and TP) is approximately 230,000 metric tons, or 30% of the total reservoir organic carbon deposits, assuming model runs for normal water year conditions on the Klamath River (Stillwater Sciences 2008). NH_4^+ and ortho-P created during summertime anoxic conditions in Iron Gate and Copco 1 reservoirs and stored in sediment pore waters may also be released and transported downstream following dam removal.

Despite this, short-term effects of dam removal on nutrients are expected to be negligible. Sediment transport modeling indicates minimal deposition of TSS in the river channel, which would include sediment-associated organic material containing TN and TP. The preferred drawdown scenario begins in early November to ensure that maximum suspended sediment concentrations will occur during winter months when flows and sediment concentrations are naturally high in the Klamath River (Stillwater Sciences 2008). Rates of primary productivity and microbially mediated nutrient cycling (e.g., nitrification, denitrification) are also expected to be low during winter months, thus particulate and organic nutrients released along with sediments are not expected to be bioavailable and should be well-conserved during transport through the middle and lower Klamath River. While NH_4^+ and ortho-P potentially released from sediment pore spaces are bioavailable, fall turnover in the reservoirs is anticipated to occur prior to reservoir drawdown, so the relatively greater concentrations of these nutrients may no longer be present in the reservoir sediments decreasing the likelihood that a large pulse of NH_4^+ or ortho-P will be transported downstream. Analysis of measured NH_4^+ and ortho-P or potential concentrations of these species in reservoir sediment pore waters should be undertaken to confirm the validity of this assumption.

In spring (after March 21), when algal blooms tend to appear in the upper Klamath River and the Project Reach (Kann and Asarian 2006), predicted sediment concentrations from dam removal will still be relatively high (300–500 mg/L TSS) in the middle and lower Klamath River (Stillwater Sciences 2008). Results of sediment transport modeling indicate minimal deposition of TSS in the river channel itself even during spring, so short-term transport of TSS is not anticipated to increase nutrient availability during the growth season. The potential for a pulse of bioavailable NH_4^+ and ortho-P released from sediment should be investigated for the spring and summer periods following the initiation of dam removal, as a reservoir pool will remain and there may be potential for stratification and anoxia in deeper waters.

2.4.2.2 Long-term Effects

While the seasonal release of nutrients associated with anoxic conditions or phytoplankton blooms in Iron Gate and Copco 1 reservoirs are likely to be alleviated following removal of the dams, the long-term effects of removing the Project dams on the annual nutrient budget of the system are uncertain. Nutrient concentrations generally decrease with distance through the Project Reach (RM 190.1 to 228.3), which appears to be primarily as result of particulate and organic nutrients settling from the water column (Section 2.4.1), but it is uncertain how annual reservoir retention and removal rates compare to rates in the free-flowing reaches that would replace the Project reservoirs (Asarian and Kann 2006a–b, Butcher 2008). Estimates of nutrient retention by riverine reaches that would replace Project reservoirs vary significantly (Butcher 2008). In particular, data and existing analyses of expected nutrient loss rates via denitrification in free-flowing reaches are currently insufficient (Butcher 2008). Because denitrification requires anoxic conditions, it is generally assumed to be negligible in the well-oxygenated gravel-bedded reaches common to the middle and lower Klamath River (Allan 1995 as cited in Butcher 2008). However, denitrification has been shown to occur beneath decaying periphyton mats (Triska and Oremland 1981), and the extent to which this occurs on the Klamath River is currently unknown.

2.4.3 Data Gaps

While multiple years of nutrient data have been collected in the Klamath Basin, our understanding of nutrient dynamics in the system remains limited. In particular, the role of the

Project dams in relation to episodic summertime increases in nutrient concentrations in the middle and lower Klamath River downstream of the dams has not been well examined. The lack of nutrient flux estimates between reservoir sediments and the water column also limit understanding of nutrient dynamics in the system. Despite these data gaps that are applicable to scenarios in which the reservoirs remain in-place, further investigation of likely nutrient retention and loss rates in the riverine reaches that would replace the Project reservoirs is a critical data gap for informing proper planning and management of potential dam removal efforts. The conceptual study plan presented in Section 5.1.4 addresses this data gap.

2.5 Dissolved Oxygen and pH

2.5.1 Current Understanding

Atmospheric oxygen is only slightly soluble in water and dissolved oxygen levels greater than 5 mg/L are generally required for fish and other aquatic life. The dissolved oxygen content of water results from photosynthetic and respiratory activities of biota in the system, and the mixing of atmospheric oxygen into the water column through wind and stream current action.

The pH of surface water is controlled primarily by atmospheric CO_2, as well as carbonate buffering, photosynthesis, and respiration. The pH of surface water is of importance because it mediates chemical speciation of many important compounds. For example, high pH levels affect the equilibrium speciation of ammonium (NH_4^+) and unionized ammonia (NH_3), the latter which is toxic to fish (USEPA 2000b). High pH levels can also increase the solubility of minerals and metals, which can adversely affect fish and other aquatic organisms. High rates of algal photosynthesis and respiration have been shown to create diel fluctuations in pH on the order of 0.5 to 1 pH units in lakes and reservoirs, as algae indirectly remove carbonic acid from the water during photosynthesis, and respiration returns carbonic acid to the water. Algal blooms and subsequent die-off can cause variations in both average daily pH and diel fluctuations in pH on a time scale of weeks (Horne and Goldman 1994, Wetzel 2001).

Total alkalinity is a measure of the system to buffer changes in pH from natural and anthropogenic sources. Typical alkalinity of freshwater ranges 20–200 mg/L, with levels below 100 mg/L indicating relatively less buffering capacity and an increased susceptibility to changes in pH. Levels below 10 mg/L indicate that the system is poorly buffered and very susceptible to changes in pH.

In situ dissolved oxygen and pH data for the Klamath River have been collected by a variety of agencies as single measurements and using continuously deployed water quality sondes. Table 8 summarizes dissolved oxygen and pH data sources used for the analysis of dam removal effects on water quality in the Klamath River.

Table 8. Dissolved oxygen and pH data and analysis sources used for the analysis of dam removal effects on water quality.

Source	Description of data or analysis	Dates available
FERC 2007	Summary of DO data from Upper Klamath Lake to the confluence with the Shasta River (RM 177.6), including profile data in Copco 1 and Iron Gate reservoirs. Includes verbal description of pH data as well.	2000–2004
FISHPRO 2000	Compilation of historical data from a variety of sources, including Upper Klamath Lake (RM 254.3 to 282.3) through the Project Reach (RM 190.1 to 228.3).	Unspecified
Karuk Tribe 2002 and 2003	Mainstem sonde monitoring data downstream of Iron Gate Dam (RM 190.1).	2000–2002
NRC 2004	Narrative summaries from a variety of sources regarding pH and DO data. Compilation of historical data from a variety of sources (1950–2001) and new data (2000–2004). The dataset is inclusive of the Klamath River basin downstream of Upper Klamath Lake.	Unspecified 1950–2004
PacifiCorp 2004a	Compilation of historical data from a variety of sources (1950–2001) and new data (2000–2004). The dataset is inclusive of the Klamath River basin downstream of Upper Klamath Lake. Compilation of historical data from a variety of sources, including Upper Klamath Lake (RM 254.3 to 282.3) through the Project Reach (RM 190.1 to 228.3).	1950–2004 Unspecified
USFWS 1997	Limited dataset for July/August at single sites on the lower Klamath and Trinity rivers.	1997

2.5.1.1 Dissolved oxygen

Dissolved oxygen levels in the Project Reach and the mainstem Klamath River vary on a seasonal and diel basis (e.g. Karuk Tribe 2002 and 2003, FERC 2007, USFWS 2008a, FISHPRO 2000). During summertime in the Project Reach, the reservoirs exhibit varying degrees of hypolimnetic anoxia as dissolved oxygen is depleted during microbial decomposition of senescent algae. Iron Gate and Copco 1 Reservoirs thermally stratify beginning in April/May and do not mix again until October/November (FERC 2007). Rapid chemical stratification occurs, with dissolved oxygen in Iron Gate and Copco 1 surface waters generally at or near saturation and levels in hypolimnetic waters reaching minimum values near 0 mg/L by July. J.C. Boyle Reservoir, a relatively long, shallow reservoir behaves more like a river than a lake and does not stratify. However, J.C. Boyle Reservoir can exhibit similarly large variations in dissolved oxygen due to conditions in the upstream Keno Reservoir (RM 233.0 to 253.1) and Upper Klamath Lake (NRC 2004). Powerhouse withdrawals, occurring at an approximately 10- or 6-meter depth in Copco 1 Reservoir and 12 meter depth in Iron Gate Reservoir, are typically from the lower epilimnion of the stratified reservoirs (NRC 2004). Dissolved oxygen levels in the lower epilimnion of Copco 1 and Iron Gate Reservoirs vary throughout the summer as the depth of the thermocline shifts, ranging from roughly 5 to 7 mg/L in summer months in Copco 1 Reservoir and from 0.5 to 6 mg/L in Iron Gate Reservoir (FERC 2007).

Dissolved oxygen modeling scenarios (PacifiCorp 2005a) comparing the existing condition (all Project dams in place) to four without-project scenarios (i.e., no Project dams; without Iron Gate Dam; without Iron Gate, Copco 1 and 2 dams; and without Iron Gate, Copco 1 and 2, and J.C.

Boyle dams) for 2001–2004 data indicate that algal trapping and the lower exchange at the air/water interface in the Project reservoirs serves to decrease dissolved oxygen levels typically beginning in April, when the reservoirs stratify, and continue through November when reservoir destratification occurs. Because Copco 1 and Iron Gate powerhouse withdrawals are located in the lower epilimnion waters, the mainstem Klamath River generally does not exhibit the extreme low levels (< 1 mg/L) of dissolved oxygen found in the bottom waters of these reservoirs. Water column aeration occurs during stream transport so that dissolved oxygen levels upstream of the Shasta River confluence (RM 177.6) in the middle Klamath River typically meet the Basin Plan criterion of 10 mg/L median annual monthly mean (USFWS 1997, NCRWQCB 2004). During much of the summer and early fall, dissolved oxygen levels throughout the middle and lower Klamath River fall below the Basin Plan minimum criterion of 8 mg/L, particularly during the night. Rare occurrences of daily dissolved oxygen minimums of 5.5 mg/L have been reported in the middle and lower Klamath River (USFWS 2008a, FERC 2007, Karuk Tribe 2002 and 2003, YTEP 2005).

Seasonally, temporary increases in dissolved oxygen levels may be associated with algal blooms, which are then followed by decreases in dissolved oxygen levels as the algal mass decomposes. It has been suggested that diel variations in dissolved oxygen, which have been measured to be as large as 1–2 mg/L throughout the Klamath River downstream of Iron Gate Dam (RM 190.1) (Karuk Tribe 2002 and 2003, YTEP 2005), are caused by daytime algal photosynthesis and nighttime bacterial respiration, the latter often driven by bacterial decomposition of senescent algae (Ward and Armstrong *in prep*, as cited by Hetrick et al. 2008).

2.5.1.2 pH

From June through October, the mainstem Klamath River downstream of Iron Gate Dam regularly exceeds the Basin Plan maximum of 8.5 (USFWS 2008a, FISHPRO 2000, Karuk Tribe 2002 and 2003, YTEP 2005, NCRWQCB 2004 and 2006a), usually during later afternoon or early evening following the period of maximum photosynthesis. In April through October, incidences of pH below the minimum Basin Plan limit of 7.0 have also been reported immediately downstream of Iron Gate Dam (RM 190.1) (PacifiCorp 2005a). Rare occurrences of pH maximums of 9.0 have been reported in the middle and lower Klamath River (USFWS 2008a, FERC 2007, Karuk Tribe 2002 and 2003, YTEP 2005). Alkalinity in the Project Reach is consistently less than 75 mg/L $CaCO_3$ equivalent (FERC 2007), indicating a low buffering capacity and a tendency for the reservoirs and downstream reaches to exhibit pH fluctuations due to photosynthesis.

2.5.2 Impacts of Dam Removal

2.5.2.1 Short-term Effects

Short term effects of dam removal on dissolved oxygen and pH are not likely to differ substantially from long-term effects, described below.

2.5.2.2 Long-term Effects

Dissolved oxygen

Dissolved oxygen modeling scenarios for 2001–2004 data indicate that substantial improvements in dissolved oxygen could occur immediately downstream of Iron Gate Dam if the Project dams are removed, with increases of 3 to 4 mg/L possible during summer and late fall (PacifiCorp

2005a). While high nutrient loads and periodic low dissolved oxygen concentrations entering the Project Reach from the Upper Klamath Basin are expected to continue, re-aeration in the mainstem river will likely restore dissolved oxygen conditions to levels that meet Basin Plan criteria, in much the same way as re-aeration under current conditions restores dissolved oxygen in the middle Klamath River by approximately the Shasta River confluence (RM 177.6). The role of photosynthesis and community respiration from periphyton growth in the free-flowing reaches of the river replacing the Project reservoirs is unknown, because nutrient cycling and resulting rates of primary productivity under a no-dams scenario is uncertain (Section 2.4.2.2). In the absence of the Project dams, PacifiCorp (2005a) predicts greater diel variations in dissolved oxygen concentrations downstream of Iron Gate Dam to the Trinity River confluence (RM 40.0), based upon the assumption that the Project reservoirs act as nutrient sinks and effectively limit algal growth downstream of the reservoirs. However, the role of the Project reservoirs as a nutrient sink during the growth season (e.g., summer and fall) has been disputed (e.g. Kann 2006, Kann and Asarian 2006, Section 2.4.1.1). The contribution of periphyton to dissolved oxygen fluctuations in the mainstem Klamath River without the Project dams may be similar to current conditions significantly downstream of Iron Gate Dam, where dissolved oxygen consistently meets the Basin Plan median annual monthly mean criterion of 10 mg/L.

pH

Removal of the dams is expected to reduce phytoplankton growth within the Project Reach, thereby reducing associated high pH and diel pH fluctuations within and immediately downstream of the Project Reach. Periphyton growth is likely to occur in the free-flowing river reaches that replace the Project reservoirs, and such growth may continue to cause diel pH fluctuations in the weakly buffered Klamath River.

2.5.3 Data Gaps

Extensive *in situ* monitoring and analysis of dissolved oxygen and pH have been conducted in the Klamath River by a variety of entities. Further exploration of the potential role of photosynthesis and respiration in the free-flowing reaches of the river that replace the Project reservoirs will support more accurate projections of dissolved oxygen and pH regimes following dam removal. These projections will be dependent on first developing a better understanding of the relationship between riverine nutrient cycling and rates of primary productivity under current conditions (Section 2.4.2.2), and then considering this relationship under a no-dams scenario.

2.6 Algae

2.6.1 Current Understanding

As primary producers, algae are critical components of riverine and lacustrine ecosystems. Their presence and abundance effect food web dynamics as well as physical water quality parameters (e.g., dissolved oxygen, pH, turbidity, and nutrients), the latter through rates of photosynthesis, respiration, and decay of senescent cells (Horne and Goldman 1994, Wetzel 2001). In the Klamath River Basin, identification of phytoplankton species and population levels in the lower, middle, and upper Klamath River has been conducted by PacifiCorp and the Yurok and Karuk Tribes from 2001 to present, while earlier phytoplankton datasets were collected in Upper Klamath Lake from 1990 to 1997 by the Klamath Tribe (Kann 1998). More recently, attached algal species, or periphyton, have also been studied in the middle and lower Klamath River.

Available sources of algal data used for the analysis of potential dam removal effects on Klamath River water quality are summarized in Table 9.

Table 9. Algal data sources used for the analysis of dam removal effects on water quality.

Source	Description of data	Dates available
Eilers 2005	Periphyton data (algae ID, percent cover, biovolume), mainstem from Iron Gate Dam to the Trinity River confluence for a single September event.	2004
Kann 1998	Phytoplankton (algae ID, biovolume, density) data in Upper Klamath Lake.	1990–1997
Kann 2008	Fish and mussel tissue samples analyzed for microcystin in the middle Klamath River and Iron Gate and Copco 1 Reservoirs	2007
Kann and Asarian 2006	Analysis and visual presentation of PacifiCorp 2004c phytoplankton data.	2001–2004
Kann and Asarian 2007	Phytoplankton (algae ID, biovolume) data in Upper Klamath Lake and Copco 1 Reservoir, May 2005 – May 2006.	2005–2006
Kann and Corum 2006 and 2007	*Microcystis aeruginosa* concentrations in Copco 1 and Iron Gate Reservoirs.	2005–2006
NCRWQCB *et al.* 2004	Periphyton data (algae ID, percent cover, biovolume), mainstem from Iron Gate Dam to the Turwar Creek confluence.	2004
PacifiCorp 2004c	Phytoplankton data (algae ID, biovolume) between Upper Klamath Lake and the confluence with the Shasta River, including Project reservoirs and several tributaries.	2001–2004
YTEP 2005, 2006, 2007, 2008a	Phytoplankton data (algae ID, biovolume) in the main stem downstream of the Trinity River.	2005–2007
YTEP 2008b	Chl-*a* in the main stem downstream of the Trinity River.	2007

2.6.1.1 Phytoplankton

Relatively high TN and TP levels flow into the Project Reach (RM 190.1 to 228.3) from the Upper Klamath River (Section 2.4.1). While phytoplankton biomass from the Klamath River upstream of the Project Reach can also be transported into the Project Reach, the abundance of readily available nutrients combined with the lacustrine environment created behind the series of four Project dams, and particularly within the larger Copco 1 and Iron Gate Reservoirs, provides ideal conditions for additional phytoplankton growth within the reservoirs themselves. This is especially applicable to nitrogen-fixing blue green algae species, which tend to thrive under warm water temperature, high nutrient, and stable water column conditions (Konopka and Brock 1978, Horne and Goldman 1994), out-competing other algal species for dominance.

Phytoplankton data for the Klamath River, spanning the period 2001–2007, indicates large summer and/or fall blooms of the nitrogen-fixing blue green algae species *Aphanizomenon flos-aquae* in the two largest Project reservoirs, Copco 1 and Iron Gate. These blooms interrupt a clear decreasing trend in blue green algae dominance and biovolume within the algal community, from sites upstream of J.C. Boyle Reservoir (RM 224.7 to 228.3) downstream through the Project Reach (Kann and Asarian 2006). For example, for the period of record, blue green algal dominance is relatively low in the shallow, low residence time (t_{res}=1.2 day, Table 2) J.C. Boyle Reservoir, where percent composition of blue green algae is less than 25% compared with upstream sites at Keno Reservoir (>80%), Link Mouth (>95%), and Upper Klamath Lake

(>98%). However, for three of the four years studied, blue green algae blooms dominate biovolume (up to >50 mm^3/L) and percent algal composition (>50%) in Copco 1 and Iron Gate Reservoirs (Kann and Asarian 2006, Kann 2006, Kann and Corum 2006 and 2007, YTEP 2006, 2007, 2008a). Additional blooms of the toxin-producing blue green algae species *Microcystis aeruginosa* occurred in three of the four years with similar periodicity. Just downstream of Iron Gate Dam (RM 190.1) and as far down as the Klamath River estuary, both *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* have been observed, albeit with decreasing importance compared to the multiple diatom species observed in the middle and lower Klamath River (Kann and Asarian 2006; YTEP 2006, 2007, and 2008a).

The presence of nitrogen-fixing algal species such as APHA has the potential to add nitrogen to the Klamath River system through transfer of N_2 from the atmosphere to algal biomass. Fixed nitrogen is incorporated into biomass using specialized cells called heterocysts and eventually released through microbial decomposition in bottom sediments as either bioavailable ammonium (NH_4^+) or the less bioavailable organic nitrogen (Section 2.4.2.2). However, nitrogen-fixation is a resource intensive process, and *Aphanizomenon flos-aquae* will typically only produce sufficient numbers of heterocysts to support nitrogen fixation when levels of inorganic nitrogen are low (Riddolls 2006, Horne and Goldman 1994, Welch and Jacoby 2004). Therefore, the presence of *Aphanizomenon flos-aquae* alone does not guarantee that N_2 fixation is a dominant nutrient pathway in the algal community. Because N:P ratios measured in the Klamath River consistently indicate that the system is nitrogen-limited with some periods of co-limitation by nitrogen and phosphorus (PacifiCorp 2004a, Hoopa Tribe 2008), some degree of nitrogen fixation is likely occurring in the reservoirs and river reaches where *Aphanizomenon flos-aquae* is observed. Nitrogen fixation could also be occurring on short time-scales (e.g., hourly, daily), during periods of intense spring or summer algal growth. Kann and Asarian (2007) measured heterocyst concentrations of three nitrogen-fixing species including *Aphanizomenon flos-aquae* in Iron Gate and Copco 1 reservoirs during summer 2005. The authors found increases in heterocyst abundance and the ratio of heterocysts to vegetative cells in the reservoirs during a July bloom, indicating the potential for nitrogen fixation in the reservoirs. No estimate of the amount of nitrogen likely to be fixed under these circumstances has been attempted, although the concurrently collected data indicates no corresponding increase in nitrogen levels in the reservoirs during the period when highest heterocyst ratios were observed (Kann and Asarian 2007). As the Kann and Asarian (2007) study represents a single study period, additional data describing whether algal nitrogen fixation occurs in the Project Reach and results in measurable nitrogen addition to the system is warranted.

Although *Microcystis aeruginosa* is not a nitrogen-fixing blue-green algae species, its importance in the river's algal community composition is due to the production of a microcystin toxin that can cause irritation, sickness, or in extreme cases, death, to exposed organisms, including humans. World Health Organization (WHO) guidelines for exposure to microcystin have been exceeded in the middle and lower Klamath River on several occasions, including a particularly intense late-summer/early-fall *Microcystis aeruginosa* bloom in September 2007 from Iron Gate Dam (RM 190.1) to the mouth of the Klamath River (RM 0.0). The *Microcystis aeruginosa* bloom was linked to increased levels of TN, TP, soluble reactive phosphorus (SRP) and TOC in the river (Section 2.4.1.2). The *Microcystis aeruginosa* bloom prompted a Yurok Tribe health advisory along affected reaches (Kann 2007a–d), and 85% of fish and mussel tissue samples collected during July through September 2007 (Kann 2008) in the middle Klamath River, including Iron Gate and Copco 1 Reservoirs, exhibited microcystin bioaccumulation. Results indicated that all of the WHO total daily intake (TDI) guideline values were exceeded, including several observations of values exceeding acute TDI thresholds (Ibelings and Chorus 2007, Kann 2008).

2.6.1.2 Aquatic macrophytes and riverine periphyton

No known quantitative or species-specific information has been collected on aquatic macrophytes in the Klamath River. In the lower Klamath River downstream of the Scott River confluence (RM 143.0), aquatic macrophytes are present only in quiet backwater areas (PacifiCorp 2005), while in the middle Klamath River between Iron Gate Dam (RM 190.1) and the Scott River, they are common in the main channel. The latter may due to the stable nature of the channel in that reach. No surveys have been conducted to determine the relative distribution or biomass of aquatic macrophytes.

In 2004, surveys of sites in the mainstem and tributaries of the middle and lower Klamath River downstream of Iron Gate Dam (RM 190.1) indicated low to moderate periphyton biomass (~0.1 to 1.1 g/m^2), dominated upstream by *Cocconeis placentula* and downstream by *Epithemia sorex (*Eilers 2005, Watercourse Engineering et al. 2005b). Growth of the attached macro-algae *Cladophora* spp. has also been recorded in the Klamath River. Under current conditions, periphyton distribution and growth in the middle and lower Klamath River may be nutrient-limited to some degree, although other factors such as flow regime and food web assemblages may also play an important role in controlling periphyton biomass (Eilers 2005, Watercourse Engineering *et al.* 2005a–b).

Disease interactions

Fish disease in the Klamath River may be indirectly linked to the growth of periphyton. *Cladophora* spp. provides habitat for the secondary host of two myxozoan parasites that cause fish diseases, *Ceratomyxa shasta* (*C. shasta*) and *Parvicapsula minibicornis* (*P. minibicornis*). *C. shasta* causes tissue necrosis and hemorrhage in infected fish, eventually leading to mortality (Bartholomew and Bjork 2007). The role of *P. minibicornis* in causing Klamath River salmonid mortality has not been examined, but the disease has been implicated as a cause of mortality in sockeye salmon (*Oncorhynchus nerka*) in British Columbia (St. Hilaire et al. 2002, Jones et al. 2003, both as cited in Bartholomew et al. 2007). Other pathogens including *Ichthyoptherius multifilis* (ICH) and *Flavobacter columnare* (columnaris) were implicated along with low flows and elevated water temperatures as the cause of a large 2002 fish kill on the lower Klamath River that resulted in the deaths of over 33,000 returning adult salmon (CDFG 2003).

Factors limiting the incidence of infection by *C. shasta* and related fish mortality are complex. Myxozoan parasites such as *C. shasta* typically have a two-host life cycle involving an aquatic invertebrate and a fish, with a spore developing in one host that is infectious to the second host (Stocking and Bartholomew 2007). The obligate invertebrate host for *C. shasta* is a polychaete worm *Manayunkia speciosa* (*M. speciosa*) that lives in *Cladophora* spp. mats. The *C. shasta* myxospores are released into the water column when infected fish carcasses breakdown post-mortality and ingested by the filter-feeding *M. speciosa*. The myxospores are then incubated and re-released as actinospores, and ingested by the fish host to complete the life cycle.

C. shasta distribution in the Klamath River appears to be at least partially controlled by distribution of *M. speciosa*. Found in lotic environments, *M. speciosa* are sessile, filter-feeding worms that build and occupy tubes projecting into the water column. *M. speciosa* are found in low velocity habitats (pools, eddies, runs) that support sand-silt substrates, which are used to construct their living tubes (Stocking and Bartholomew 2007). In the Klamath River, *M. speciosa* has been observed at extremely high densities ($10^3/m^2$) in association with *Cladophora* spp. blooms (Stocking and Bartholomew 2004). *Cladophora* spp. affixes to boulder and bedrock surfaces, forming dense mats that trap and collect sand-silt substrates (OSU 2004). During the summer, *Cladophora* spp. grows into long, filamentous tufts that can reach several meters in length and dominate primary producer biomass (Power et al. 2008). Invertebrates, such as chironomid midges, graze the tufts into short (0.5–1 cm) mats that provide a protected environment for *M. speciosa* tube construction and thus serve as preferred microhabitat (Power et al. 2008, Stocking and Bartholomew 2007). The short mats are reduced to loose detritus by the late summer and then, after winter and early spring flood scour, to individual basal cells, which initiate vegetative growth into filamentous tufts the following late spring and early summer.

Based on a review of several literature sources, the high incidence of *C. shasta* infection in the Klamath River appears to be the result of multiple factors that combine to increase overall host availability for the parasite and support highly favorable incubation and infection conditions in the hosts. Water regulation and diversions within the Klamath River Basin, including but not limited to the four Project dams being considered for removal, have resulted in reduced summer baseflow and low flow conditions that are more prolonged than pre-regulation conditions (Section 2.1; NRC 2004, Hecht and Kamman 1996). The flow alterations may be responsible for creating large areas of low-velocity, low-disturbance habitat in the middle and lower Klamath River that is ideal for supporting high densities and frequency of occurrence of *M. speciosa* (Stocking and Bartholomew 2004, 2006). *M. speciosa* populations have been found to be higher at the inflows of Project reservoirs and immediately downstream of Iron Gate Dam (Stocking and Bartholomew 2007, Stocking 2006) where flow regime and substrate are expected to be relatively more stable than in riverine reaches. Recent laboratory experiments by Bartholomew and Bjork (2007) indicate that habitat disturbance such as mechanical disruption or desiccation of substrate decreases the survival of *M. speciosa* populations.

If periphyton distribution and growth in the middle and lower Klamath River is nutrient limited (Eilers 2005, Watercourse Engineering *et al.* 2005a–b), the increase in bioavailable nitrogen and phosphorus levels during the growth season due to dam-related alterations in nutrient cycling (Section 2.4.1.1) could support relatively higher growth of *Cladophora* spp. in the river. Furthermore, increased food availability for *M. speciosa* from high rates of phytoplankton growth in the Project reservoirs may also support high levels of polychaete host availability for *C. shasta*. While it has been suggested that earlier seasonal flow peaks created by Project dam operations may reduce late spring scouring of *Cladophora* spp., functionally extending the growing season of the periphyton mats, it is not clear whether this physical habitat alteration has produced a demonstrable effect on *Cladophora* spp. distribution in the river, resulting *M. speciosa* colonization, or *C. shasta* infection rates.

In addition to providing increased host availability, current conditions in the Klamath River also appear to support high incubation and infection rates for *C. shasta* within the two parasite hosts. The rate of *C. Shasta* infection for *M. speciosa* is lower upstream of Iron Gate Dam and higher downstream of the dam (OSU 2004, Stocking and Bartholomew 2007). Summer water temperatures in the middle and lower Klamath River are higher than those measured in the upper Klamath River or in proximal coastal rivers (Bartholow 2005), which may create more favorable incubation conditions for *C. shasta* within the polychaete hosts or higher infection rates within already thermally stressed Chinook salmon (Foott et al. 2003 and 2004, OSU 2004, Yurok Tribal Fisheries Program 2005, CDFG 2003). However, the effect of water temperature on *C. shasta* incubation and infection rates in the Klamath River is not yet well understood. Recent laboratory experiments by Bartholomew and Bjork (2007) showed that temperature has an inverse relationship with *C. shasta* actinospore longevity. Actinospores were relatively short-lived at 20°C (68 °F), a temperature that is within the typical range of summer conditions on the middle and lower Klamath River (Section 2.2.1). Additionally, while polychaete survival was stable at 5°C (9 °F) over 12 weeks, there was almost no survival at 20°C (68 °F) over the same time period. The decreased survival at warmer temperatures may have been due to limited food availability for *M. speciosa* in the experimental chambers (Bartholomew and Bjork 2007) and further research is needed to isolate temperature effects from other potential confounding factors. The authors also investigated the relationship between flow rate and infection rate for *M. speciosa* and salmonids (i.e., Chinook salmon and rainbow trout). Experimental results indicated that at moderate flow conditions (0.05 m/s [0.2 ft/s]), mean polychaete densities were higher, polychaetes had a lower *C. shasta* infection prevalence, and salmonids experienced longer mean day-to-death as compared with slower flow (0.01 m/s [0.03 ft/s]) conditions. The authors postulated that at the moderate flow levels tested, nutrients are transported and wastes are carried away from the *M. speciosa* community without disturbance to habitat substrate. For context, *M. speciosa* in the Klamath River has been observed at 0.01 to 0.15 m/s (0.03 to 0.5 ft/s) in sand substrate and 0.01 to > 0.3 m/s (0.03 to > 1.0 ft/s) in *Cladophora* spp. mats.

Overall then, the limiting factor for *C. shasta* in the Klamath River has not yet been determined. While recent experiments by Bartholomew and Bjork (2007) have begun to elucidate the relationship between flow, temperature, substrate, host infection rates, and *C. shasta* prevalence in the Klamath River, further research is required to fully understand the complexity of the disease interactions.

2.6.2 Impacts of Dam Removal

2.6.2.1 Short-term Effects

Short-term effects of dam removal on phytoplankton and periphyton growth in the middle and lower Klamath River are expected to be negligible. The preferred drawdown scenario begins in early November when flows and sediment concentrations are naturally high (Stillwater Sciences 2008) and rates of primary productivity and microbially mediated nutrient cycling (e.g., nitrification, denitrification) are low. Therefore, organic carbon and the associated organic nitrogen and phosphorus released along with sediments trapped behind the dams are not expected to be bioavailable and should be well conserved during winter transport through the mainstem Klamath River (Section 2.4.2.1).

In spring (after March 21), when algal blooms tend to appear in the upper Klamath River and the Project Reach (Kann and Asarian 2006), predicted sediment concentrations from dam removal will still be relatively high (300–500 mg/L TSS) in the middle and lower Klamath River (Stillwater Sciences 2008) with minimal deposition of TSS in the river channel itself. Thus, short-term transport of TSS due to dam removal is not anticipated to increase nutrient availability for algal or aquatic macrophyte growth regardless of season. While a potential pulse of bioavailable NH_4^+ and ortho-P from reservoir sediment pore spaces could stimulate spring and summer algal or aquatic macrophyte growth in the short-term (Section 2.4.2.1), high TSS levels may cause light limitation for riverine algae, periphyton, and aquatic macrophytes resulting in a relative decrease in primary productivity in the middle and lower Klamath River during the spring period immediately following reservoir drawdown.

2.6.2.2 Long-term Effects

Based on available information, Copco 1 and Iron Gate Reservoirs appear to enhance the growth of blue green algae, including the toxin-producing *Microcystis aeruginosa*, by providing the warm, stable water column conditions within which these species thrive. While nutrient inputs from the Upper Klamath Basin will not be affected by dam removal, the absence of lacustrine conditions supported by the four Project dams should allow blue green algal dominance to be replaced by that of diatoms and green algae in the Project Reach. *Microcystis aeruginosa* prevalence should decrease dramatically in the Project Reach due to the lack of available habitat. However, as the long-term effects of removing the Project dams on the nutrient budget of the system are uncertain (Section 2.4.2), effects on overall algal growth are also uncertain. In particular, changes in nutrient dynamics and replacement of lacustrine phytoplankton with riverine periphyton could have unexpected consequences for algal populations within and downstream of the Project Reach. Periphyton growth could be quite high following dam removal since nutrient loads from the upper Klamath Basin would still be relatively high.

While there is little evidence that the hydrological regime would change significantly under a no-dams scenario (Section 2.1.2.2), flow variability during storm flow events is likely to increase downstream of Iron Gate Dam and could increase scouring of periphyton during late spring storm events. Many species of periphyton are known to be sensitive to high flow velocities (Horne and Goldman 1994), and the increased scouring of *Cladophora* spp. mats early in the growth season could decrease habitat availability for *M. speciosa* later in the summer, and ultimately decrease the prevalence of *C. shasta* in the system. Increased flow variability might also decrease the large areas of habitat that are ideal for supporting high densities and frequency of occurrence of *M. speciosa*. Lack of seasonal nutrient releases from the reservoirs would also decrease periphyton habitat availability for *M. speciosa*, assuming that periphyton growth and distribution is nutrient limited. Overall however, the complexity of *C. shasta* disease interactions in the Klamath River means that it is difficult to predict the long-term prevalence of the myxosporan parasite following dam removal. Regardless of limiting factors for *C. shasta*, the congregation of fish in the middle Klamath River immediately downstream of Iron Gate Dam would likely be reduced in a no-dams scenario, decreasing the likelihood of concentrated disease transmission just downstream of the Project Reach and potentially throughout the middle Klamath River.

2.6.3 Data Gaps

Knowledge of the contribution of reservoir nitrogen-fixing blue-green algae to overall nitrogen levels in the middle and lower Klamath River is limited to a single study undertaken in 2005 and is therefore a current data gap. While the available information suggests that nitrogen fixation occurs at low levels in Copco 1 and Iron Gate Reservoirs and does not add measurable amounts of nitrogen to the Klamath River system (Kann and Asarian 2007), additional data beyond a single sampling year would improve our understanding of the potential effects of dam removal on riverine nutrient cycling. Ongoing studies at the University of California, Santa Cruz, regarding nutrient limitation for blue-green algal species in the Project reservoirs (Moisander *in prep*) are expected to elucidate the likely importance of these species to reservoir nitrogen cycling and potentially support predictions of altered nutrient cycling in the absence of the Project dams. In anticipation of forthcoming results from these studies in early 2009, a conceptual study design has not been developed to address the contribution of blue-green algae to reservoir nitrogen cycling for this water quality synthesis.

The available dataset lacks information on the spatial and temporal distribution of aquatic macrophytes in the middle and lower Klamath River. Since no reports of excessive aquatic macrophyte biomass have been noted in the available data record, they likely do not play a dominant role in nutrient cycling or primary productivity in the middle and lower Klamath River. However, this assumption should be tested prior to dam removal efforts in order to better support predictions of dam removal effects on long-term primary productivity in the river and to serve as baseline data should the dams be removed. The conceptual study plan presented in Section 5.1.1 addresses this data gap.

It is not clear whether the primary factor limiting periphyton growth in the Klamath River under current conditions is nutrient availability or flow and physical habitat structure, thus it is not known how the limiting factor(s) may change if the Project dams are removed. Since diel variations in dissolved oxygen and pH have been linked to primary productivity downstream of the Project Reach (Section 2.5), it is apparent that photosynthetic activity from algae and periphyton is currently affecting Klamath River water quality. Further investigation of the relationship between riverine nutrient cycling and rates of primary productivity under current conditions will support a better understanding of the likely relationship under a no-dams scenario. The conceptual study plan presented in Section 5.1.4 addresses this data gap. Ongoing studies by the Yurok Tribe to increase the precision of existing Klamath River nutrient budgets (S. Corum pers. comm.), while not able to inform a mechanistic understanding of nutrient cycling in the riverine reaches of the middle and lower Klamath River, are expected to improve our understanding of seasonal and annual nutrient cycling and may also support increased knowledge of the potential for periphyton nutrient uptake rates.

Finally, while recent experiments by Bartholomew and Bjork (2007) have begun to elucidate the relationship between flow, water temperature, substrate, and host infection rates on *C. shasta* prevalence in the Klamath River, further research is required to fully understand the complexity of the disease interactions. Confounding factors in the laboratory studies (e.g., food availability for laboratory *M. speciosa* populations) rendered the results somewhat inconclusive for determination of *C. shasta* primary limiting factors. Continuation of the experimental set-up described in Bartholomew and Bjork (2007) under refined laboratory conditions and a wider range of flows may be sufficient to determine the primary limiting factor for *C. shasta* infection rates. However, the conceptual study plan presented in Section 5.1.1 has been developed as an alternative or potentially supplemental approach to addressing this data gap.

2.7 Summary of potential effects of the removal of Iron Gate, Copco 1, Copco 2, and J.C. Boyle dams on Klamath River water quality

Based on the synthesis of available information presented in Sections 2.1 through 2.6, the following is a summary of potential short-term and long-term effects that removal of the four Project dams may have on hydrology and water quality of the middle and lower Klamath River, and that portion of the Project Reach extending into the upper Klamath River:

<u>Potential short-term effects</u>

- Short-term, high suspended sediment loads are expected in the middle and lower Klamath River in the short-term (1–2 years) following dam removal. Estimated release of organic carbon (including nitrogen and phosphorus) is approximately 230,000 metric tons, or 30% of the total reservoir organic carbon deposits, assuming model runs for normal water year conditions on the Klamath River. As minimal sediment deposition is expected in the river channel downstream of the Project Reach, the sediment-associated carbon, nitrogen and phosphorus should be well-conserved through the river and seasonal nutrient availability is not expected to be impacted by dam removal. Screening of reservoir sediments indicates low levels of a variety of contaminants (e.g., metals, VOCs, pesticides and herbicides, dioxin), therefore toxicity caused by exposure to these contaminants in the short-term following dam removal is not expected to be problematic.

- Based on their limited active storage capacity, removal of the Project dams is not expected to impact long-term hydrology of the middle and lower Klamath River (not including the Project Reach) on an annual basis. However, seasonal flow variability in the middle Klamath River immediately downstream of Iron Gate Dam is likely to increase, particularly during winter and spring storm events. Within the Project Reach, dam removal will reduce the mean summer hydraulic residence time from approximately several weeks to several days.

<u>Potential long-term effects</u>

- As is the case for potential short-term effects (see first bullet above), minimal sediment deposition is expected in the river channel downstream of the Project Reach, therefore sediment-associated carbon, nitrogen, phosphorus and measured contaminants (e.g., metals, VOCs, pesticides and herbicides, dioxin) released during dam removal are not expected to be problematic in the long-term.
- In the long-term, decreased transit time of water in the Project Reach is expected to result in the following:
    - Decreased late summer and fall water temperatures in middle and lower Klamath River, with the greatest relative cooling (typically about 2–4 °C [4–7°F]) occurring just downstream of Iron Gate Dam, diminished amounts of cooling occurring with distance downstream, and typically negligible cooling by the confluence with the Salmon River. Immediately upstream of the confluence with the Scott River, dam removal is likely to reduce typical temperatures by roughly 2 °C (4 °F). The predicted summer and fall water temperature impacts do not include potential climate change effects, which remain unclear based on our current understanding of factors controlling regional climate such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Section 1).
    - Increased springtime water temperatures in the middle and lower Klamath River, with the greatest relative warming (typically about 1–3 °C [2–5°F] occurring just downstream of Iron Gate Dam, diminished amounts of warming occurring with distance downstream, and typically negligible warming by the confluence with the Salmon River. Immediately upstream of the confluence with the Scott River, dam removal is likely to increase typical springtime water temperatures by roughly 1–2 °C (24 °F). The predicted springtime water temperature impacts do not include the potential impacts of climate change (Section 4).
    - Alleviated seasonal release of nutrients (NO_3^-, NH_4^+, ortho-P) associated with anoxic conditions or phytoplankton blooms in the Project reservoirs.
    - Decreased or absent seasonal blooms of blue-green algae, including the toxic *Microcystis aeruginosa*.
    - Increased dissolved oxygen levels (up to 3–4 mg/L during summer and late fall) immediately downstream of the Project Reach and significantly fewer instances of dissolved oxygen falling below Basin Plan criteria.

  - Reduced high pH (>8 pH units) and diel pH fluctuations (> 1 pH unit) within and immediately downstream of the Project Reach.
- In the long-term, the lack of sediment trapping behind the Project dams is expected to result in the following:
  - Episodic increased levels of TSS and turbidity in the middle Klamath River during late spring and summer due to transport of algae blooms from the upper Klamath River.
  - Increased wintertime TSS and turbidity in the middle and lower Klamath River with peak levels (>50 NTU and 150 mg/L TSS) associated with storm events.
- The long-term effects of removing the Project dams on the annual nutrient budget of the system are uncertain. This includes the role of denitrification and periphyton growth in the free-flowing reaches of the river replacing the Project reservoirs, because nutrient cycling and resulting rates of primary productivity under a no-dams scenario remain uncertain. Thus, impacts to overall periphyton growth and the potential for disease interactions from dam removal are currently uncertain.

3 KLAMATH RIVER ESTUARY WATER QUALITY SYNTHESIS

The Klamath River estuary at the terminus of the Klamath River is located along the Pacific Coast approximately 32 km (20 mi) south of Crescent City in Northern California. The estuary receives water from the Klamath, Scott, Shasta, Salmon and Trinity River watersheds which together comprise approximately 31,080 km^2 (approximately 12,100 mi^2). Tidal exchanges are commonly assumed to influence the lower 6.5 km (4.0 mi) of the Klamath River. From the mouth (RM 0) to approximately RM 2, the estuary is approximately 1.2 km (0.75 mi) wide and is divided into two portions; the main channel on the northern side, and a network of channels and gravel bars called the south slough. A sand bar typically exists between two bedrock formations to the north and south of the river mouth, with the mouth itself typically located either on the far northern or far southern end of the bar (Wallace 1998). As is the case for the mainstem Klamath River, the estuary exhibits variable flows and residence time based upon season. Rainfall and snowmelt during winter and spring months increases flows and water exchanges in the estuary and periods of low flow occur during summer and fall months. The estuary mouth has occasionally closed during summer low flow periods (Hiner 2006).

The Klamath River estuary is essential in the life cycles of anadromous salmonids found in the system, including spring and fall-run Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*O. kisutch*), steelhead trout (*O. mykiss*), and coastal cutthroat trout (*O. clarki clarki*). The estuary may also provide vital habitat during various life history stages for other species of importance such as eulachon (*Thaleichthys pacificus*), Pacific lamprey (*Lampetra tridentata*), and green sturgeon (*Acipenser medirostris*) (Hiner 2006, Wallace 1995). While historical accounts indicate that juvenile salmon in the Klamath estuary during late summer and early fall averaged six to seven inches long (Snyder 1931), recent studies conducted by the Yurok Tribe and CDFG have observed smaller average lengths (Wallace 1993, Hiner and Brown 2004). While the latter could be due to inherent differences between hatchery and wild stock, recent studies also indicate that juvenile Chinook salmon arrive earlier in the summer than historical evidence suggests and only undertake a brief residency ranging between 8.7–16.2 days on average (Wallace 2000).

Water quality within the estuary is likely a critical factor in the suitability of estuarine habitat for juvenile salmonids. Although the Klamath River estuary is located far downstream of the Project Reach, water quality in the estuary may be affected by the presence of the upstream Project dams. However, to date, no study has focused on the potential effects of the Project dams on estuary water quality, or on impacts to the estuary should the dams be removed. The following sections are a summary of existing hydrology and water quality information for the Klamath River estuary, compiled from a variety of agency, tribal, and academic sources, along with a brief discussion of the potential impacts on estuarine water quality from removal of the four Project dams.

3.1 Hydrology

3.1.1 Current Understanding

The Shasta, Scott, Salmon, and Trinity rivers contribute approximately 44% percent of the Klamath River Basin's mean annual runoff and have a substantial influence on the timing of peak and low flow rates within the lower Klamath River (FERC 2007) and, accordingly, the Klamath River estuary (Table **3**). Flow in the estuary normally peaks during the winter and/or early spring from snowmelt and rainfall runoff, with flows that can exceed 2,830 m^3/s (100,000 cfs) during wet years (USGS Klamath River near Klamath [gage #11530500]). Low flows within the estuary (i.e., 28–113 m^3/s [1,000–4,000 cfs]) typically occur during the late summer or early fall, after snowmelt and before runoff from fall storms originating over the Pacific Ocean move across the watershed.

When the estuary mouth is open, water levels in the estuary and lower Klamath River are tidally influenced as far upstream as RM 4. Tidal dynamics in the Klamath River estuary are mixed on a semidiurnal basis typical of the western United States (NOAA 2008a,b). Mouth closure, caused by formation of a sand berm across the mouth of the estuary, is a function of off-shore and along-shore wave power and sediment supply, freshwater inflows, the tidal prism of the estuary, and morphological characteristics of the inlet (Escoffier 1940, Brunn 1966, O'Brien 1971, Barnes 1980). The historical frequency and duration of mouth closure in the Klamath River estuary has not been documented.

3.1.2 Impacts of Dam Removal

3.1.2.1 Short-term Effects

Short term effects of dam removal on hydrology in the estuary are not likely to differ substantially from long-term effects, described below.

3.1.2.2 Long-term Effects

Comparisons of contemporary flows in the estuary to those existing prior to the construction of the four dams along the mainstem Klamath River are not easily constructed from hydrologic records due to lack of pre-dam flow data. Therefore, expected long-term effects of dam removal on estuarine hydrology must be derived from an understanding of current dam-related effects on estuarine hydrology. The four reservoirs presently have limited active storage and provide minimal flood attenuation for larger peak flood events. Maximum active storage in the four Project reservoirs is less than $1.5x10^7$ m^3 (12,000 acre-feet) (Table 2), or less than 1% of annual runoff to the Klamath River estuary (Table **3**),, indicating that they do not provide sufficient storage to alter the long-term hydrology of the estuary. In contrast, flow in the Trinity River is regulated through storage at Trinity Lake and Lewiston Reservoir and includes significant flow diversion out of the Trinity River Basin to the Sacramento River Basin (BOR 2008).

Water temperature in the lower river has been modeled with respect to dam-related impacts (PacifiCorp 2005a) and may serve as a suitable proxy for assessing hydrologic impacts of the dams to the lower river and by extension, the estuary. Results of water temperature modeling indicate that the water stored behind the dams does impact water temperature in the mainstem Klamath River on a seasonal basis, as discharge water temperatures reach equilibrium with the ambient air temperatures. However, according to the model, these impacts are alleviated upstream of the confluence of the Salmon River, or approximately 106 km (66 mi) upstream of the estuary.

The combination of significant tributary flow inputs to the estuary beyond those of the dam-influenced mainstem Klamath River (Table **3**), the lack of long-term water storage capability within the four mainstem reservoirs, and PacifiCorp (2005a) temperature modeling results indicating alleviation of seasonal dam-induced water temperature effects (used here as a proxy for hydrology effects) far upstream of the estuary (Section 2.2.1) suggest that the dams' current impact on estuarine hydrology is not expected to be significant on an annual basis (see Section 2.1.2.2). Therefore, dam removal is not expected to have a long-term impact on estuarine hydrology.

However, no study to date has focused on the factors currently controlling estuarine seasonal hydrology, particularly during summer low-flow conditions when current theoretical hydraulic residence time of water in the Project Reach can range as high as approximately 60 days (NRC 2004, FERC 2007). Small changes in summer baseflows by the current operation of dams and water diversions on the Klamath and Trinity Rivers may affect mouth closure dynamics in the Klamath River estuary. A sand bar that closes completely and isolates the estuary from the ocean for more than a few days could be detrimental to water quality and biota by allowing water temperatures to increase beyond optimal growth thresholds or critical thermal maxima for outmigrating salmonids and remain at untenable levels until the mouth is breached again. While the operation of Project dams may cause a small but functionally significant decrease in summer low-flows and a corresponding increase in the potential for estuary mouth closure, the likelihood of this effect has not been tested. Thus, it is currently unknown whether changes to hydrology in the Klamath River caused by dam removal will have a discernable effect on the frequency of mouth closure during summer months.

Alterations to morphological characteristics of the Klamath River estuary as a result of dam removal are also likely to be important factors in the consideration of how dam removal will impact seasonal hydrology in the Klamath River estuary. Long-term deposition of sediment in the estuary may increase following dam removal, since the dams will no longer trap sediment (Section 3.3.2.2). Increased sediment deposition could decrease the size of the salt wedge, either by increasing the frequency of mouth closure, or by elevating the bottom of the estuary above portions of the tidal range when the mouth is open. Scouring of current estuarine sediment deposits may also occur during high sediment transport immediately following dam removal. As these sediment transport processes, or others that have not yet been considered with respect to dam removal, have the potential to effect morphology of the estuary, they may also impact seasonal hydrology in the Klamath River estuary in the long-term.

3.1.3 Data gaps

Further investigation of factors controlling estuarine hydrology during summer low-flow conditions is warranted to better determine the long-term effects of dam removal. Linking summertime low-flow hydrology to the current morphology of the estuary and the potential for mouth closure would help to improve our understanding of the potential effects of dam removal on seasonal estuarine hydrology. The conceptual study plan described in Section 0 addresses this data gap.

3.2 Water temperature and salinity

3.2.1 Current Understanding

Water temperature and salinity have been monitored in the Klamath River estuary by CDFG (Wallace 1998) and most recently by USFWS (Hiner 2006) and the Yurok Tribe (YTEP), with support from the North Coast Regional Water Quality Control Board. Data sources for salinity and temperature data in the Klamath River estuary are summarized in Table 10.

Table 10. Water temperature and salinity data sources for the Klamath Estuary (in addition to Table 4).

Source	Description of Data	Dates available
Hiner 2006	Bi-weekly temperature and salinity at three cross sections and several other sites.	2001–2003
Wallace 1998	Monthly to bi-monthly salinity and temperature data from at least four transects	1991–1994
YTEP 2005	Sporadic summertime continuous temperature and salinity data at three sites on the surface and at depth. Surface and at depth measurements on four days for three cross sections.	2004
YTEP and NCRWQCB 2005	Continuous monitoring of temperature and salinity at six sites during a pulse flow from the Trinity River in August.	2004

Water temperatures in the estuary from December through April range roughly 5–2 °C (41–54 °F) (Hiner 2006). In summer and fall months, warmer air temperatures and lower flows result in increased water temperatures. Under low-flow summertime conditions, water temperatures in the estuary have been observed to range 20–24°C (68–75.2 °F)(Wallace 1998) or greater than 24°C (75.2 °F) (Hiner 2006), exceeding optimal growth thresholds as well as critical thermal maxima for Coho, Chinook salmon, and steelhead (Brett 1952, Armour 1991, Stein et al 1972, Frissell 1992, McGeer et al. 1991). Estuarine water temperature is linked to salinity, upstream hydrology, and periods of mouth closure because when the estuary mouth is open, denser salt water from the ocean sinks below the lighter fresh river water, resulting in a salt wedge that moves up and down the estuary with the daily tides (Horne and Goldman 1994, Wallace 1998, Hiner 2006). The salt wedge results in thermal stratification of the estuary with cooler, high salinity ocean waters remaining near the estuary bottom, and warmer, low salinity river water located near the surface. Upstream hydrology can affect the location of the salt water wedge and thus impact thermal structure in the estuary. For example, during pulse flows released from the Lewiston Dam on the Trinity River in August 2004, the upstream extent of the salt wedge moved downstream approximately one mile (YTEP 2005, YTEP and NCRWQCB 2005). In the Klamath River estuary, mouth closure has been reported to reduce the size of the salt water wedge, decrease overall salinity, and subsequently increase water temperatures in the estuary (Hiner 2006).

3.2.2 Impacts of Dam Removal

3.2.2.1 Short-term Effects

Following dam removal, deposition of sediments currently stored behind the Project dams in the estuary may slightly increase the risk of temporary closure of the estuary mouth, thus affecting short-term, hydrology, water temperature and salinity in the estuary. This possibility is discussed further in Section 3.3.2.1. Likewise, deposition of sediments in the estuary could also alter short-term estuary morphology, potentially decreasing water column depth and reducing saline coldwater habitat availability until sediments are displaced or actively removed from the estuary.

3.2.2.2 Long-term Effects

Water temperature in the lower Klamath River has been recently modeled with respect to dam-related impacts (PacifiCorp 2005a) (Section 2.2.1). Results of the water temperature modeling indicate that the water stored behind the dams impacts water temperature in the lower river on a seasonal basis, as discharge water temperatures reach equilibrium with the ambient air temperatures. According to the model, these impacts decrease in magnitude with distance downstream of Iron Gate Dam, and they are not evident by RM 66.9 (upstream of the Salmon River confluence). Therefore, it is unlikely that removal of the Project dams will significantly affect the temperature of water entering the estuary.

As with estuarine hydrology (Section 3.1.2.2), alterations to morphological characteristics of the Klamath River estuary as a result of dam removal are likely to be important factors in the consideration of how dam removal will impact water temperature in the Klamath River estuary. Long-term deposition of sediment in the estuary may increase following dam removal, since the dams will no longer trap sediment (Section 3.3.2.2). Increased sediment deposition could decrease the size of the salt wedge, either by increasing the frequency of mouth closure, or by elevating the bottom of the estuary above portions of the tidal range when the mouth is open. Scouring of current estuarine sediment deposits may also occur during high sediment transport immediately following dam removal. As these sediment transport processes, or others that have not yet been considered with respect to dam removal, have the potential to affect estuary morphology, they may also impact seasonal water temperatures in the Klamath River estuary in the long-term.

3.2.3 Data Gaps

Further investigation of factors controlling estuarine hydrology, morphology, and mouth closure dynamics during summer low-flow conditions is warranted to better inform decision making regarding the short-term and long-term effects of dam removal on the Klamath River estuary. In particular, linking summertime low-flow hydrology to the current morphology of the estuary and the potential for mouth closure would help to improve our understanding of the potential effects of dam removal on estuarine water temperature during summertime low-flow periods. The conceptual study plan described in Section 5.1.5 addresses this data gap.

3.3 Sediment and turbidity

3.3.1 Current Understanding

Peak suspended sediment loads to the Klamath River estuary are expected to occur during winter and/or early spring high flow periods. While sediment loads have not been reported for the estuary itself, turbidity measurements in small tributaries (e.g., McGarvey, Den, Blue, and Turwar creeks) immediately upstream or within a few river miles upstream of the estuary exhibit peak values during winter high flow periods (i.e., storm events), with measured values exceeding 500 NTU during December through February 2004 (YTEP 2005). Periodic simultaneous measurements of total suspended solids (TSS) and turbidity are also reported for these tributaries, exhibiting a linear relationship between TSS and turbidity ($r^2 = 0.89$, $p<0.0001$, Figure 2-5), and suggesting that peak TSS is also likely to enter the Klamath River estuary during high-flow periods of winter and early spring.

During late spring through early fall, when average rates of precipitation in the Klamath Basin are relatively lower, TSS and turbidity in the Klamath River estuary is expected to decrease. While there is limited TSS and turbidity data for the estuary itself, analysis of available TSS and turbidity data for the mainstem Klamath River suggests that both parameters decrease longitudinally from upstream to downstream between Link River at Klamath Falls (RM 253.1) and Iron Gate Reservoir (RM 190.1) (PacifiCorp 2004b). Just downstream of Iron Gate Reservoir, TSS and turbidity have been observed to be generally low (e.g., <5 mg/L and <5

NTU). This suggests that sediments are being intercepted and retained by the dams, leaving low overall TSS levels for transport further downstream and into the estuary during these months. Further downstream in the estuary, summer and fall TSS levels have been observed to be equal to or lower than those measured at sites further upstream (YTEP 2008b).

Algal blooms occurring within and upstream of the estuary have the potential to cause spikes in turbidity and TSS in the estuary itself. This occurred during the extensive algal bloom detected throughout at least 40 river miles of the lower Klamath River in September 2007 (Section 2.6.1.1). In the lower estuary, increases in nutrient levels and phytoplankton concentrations were correlated with an increase in TSS from 2.2 mg/L on August 21, 2007 to 9.0 mg/L on September 18, 2007, but increases in nutrients, phytoplankton levels, and TSS during that period were measured as far upstream as the Trinity River confluence (RM 40.0) (data from additional upstream locations are not yet available). Thus, the observed increase in estuarine TSS appears to have been influenced by algal growth upstream of the estuary as well.

Based on analyses conducted to date (Eilers and Gubala 2003, GEC 2006, Stillwater Sciences 2008), a large volume (11.1 to 15.5 million m^3 [14.5 to 20.3 million yd^3], Section 2.3.1) of accumulated sediment material is currently behind the Project dams. Discounting 5% of the existing sediment deposits from the total volume due to assumed reservoir-associated algal productivity (Section 2.3.1), rough calculations suggest that an average of 0.50 to 0.68 million m^3/yr (0.66 to 0.88 million yd^3/yr) of sediment would have been transported through the estuary during roughly the past 50 years in the absence the dams. Sediment transport is assumed to have occurred primarily during high flow periods. This is an average estimate only and it is expected that inter-annual sediment loads vary with precipitation conditions. While current estuary morphology exhibits a deep, main channel for conveying the majority of flow and suspended sediment load, a general lack of understanding regarding sediment dynamics in the estuary means that it is difficult to predict whether an average annual sediment load of this magnitude would have resulted in altered estuarine morphology (as a cumulative effect), in the absence of the dams.

However, diminished transport of sediment originating from the upper Klamath Basin over the past several decades has likely decreased long-term nutrient deposition through the estuary[1]. Surface sediment composition of a single, recent core collected along the edge of the main channel in the Klamath River estuary showed very low carbon and nitrogen content and a relatively low content of phosphorus compared to cores from four other lake or reservoir locations upstream of the Project dams (e.g., in Lake Euwana just downstream of Upper Klamath Lake, and in Wilson Reservoir and upstream of Harpold Dam on the Lost River) (Eilers and Raymond 2005). Because estuary sediments are typically rich in organic matter and sequestered nutrients (Horne and Goldman 1994), these results suggest that, in addition to sediment interception, long-term nutrient retention is also occurring in the Project reservoirs and may be contributing to decreased sediment nutrient levels in the Klamath River estuary.

[1] This does not include increased sediment transport caused by logging activities and land management in the lower Klamath Basin, which is not affected by the upstream dams.

3.3.2 Impacts of Dam Removal

3.3.2.1 Short-term Effects

Current sediment transport modeling efforts indicate that a substantial fraction (~ 30%) of the existing sediment deposits within the reservoirs would be released downstream during and/or following dam removal (Stillwater Sciences 2008). This would result in high short-term (1–2 years) suspended sediment loads downstream of the dams, including the estuary. Modeling efforts for the mainstem river extend to Orleans (~RM 59), and thus current estimates for maximum suspended sediment concentrations do not account for sediment dynamics within the estuary itself. The preferred drawdown scenario begins in early November to ensure that maximum suspended sediment concentrations will occur during winter months when flows and sediment concentrations are naturally high in both the mainstem river and the estuary, however in spring (after March 21) predicted sediment concentrations will still be relatively high (300–500 mg/L TSS) downstream of Orleans (~RM 59) (Stillwater Sciences 2008).

Based on multiple drawdown scenarios, no discernable sediment deposition is predicted downstream of Iron Gate Dam (Stillwater Sciences 2008), indicating minimal potential for deposition in the river. However, estuary-specific sediment dynamics have not been thoroughly investigated and thus the possibility of short-term sediment deposition in the salt-water mixing zone of the estuary requires further study. Significant sediment deposition in the estuary would decrease overall depth at certain locations, reducing the volume of the cool water pool in the bottom portion of the lagoon, or affect the formation of the sand berm, causing longer duration or earlier mouth closure. If newly deposited sediments are displaced by subsequent high flows or actively removed from the estuary within the 1–2 years following dam removal, the effect may be only temporary.

3.3.2.2 Long-term Effects

Alterations to morphological characteristics of the Klamath River estuary as a result of dam removal may have direct effects upon long-term hydrology, water temperature, and salinity in the Klamath River estuary, as well as the frequency and duration of mouth closure. Long-term deposition of sediment in the estuary may increase following dam removal, since the dams will no longer trap sediment upstream. As with the potential short-term effects of sediment deposition, increased sediment deposition in the long-term could decrease the size of the salt wedge, either by increasing the frequency of mouth closure, or by elevating the bottom of the estuary above portions of the tidal range when the mouth is open. Long-term decreases in the availability of thermal refugia in the estuary during summer months could become a limiting factor for Klamath River anadromous salmon populations

Following dam removal, renewed deposition of organic sediments transported from upstream will also potentially affect long-term nutrient cycling and sequestration in the estuary. Increased carbon, nitrogen, and phosphorus content of sediments moving through, and potentially being deposited within, the Klamath River estuary may increase primary productivity, with possible ramifications for the estuarine food web (Section 3.4).

3.3.3 Data Gaps

Factors controlling estuarine sediment dynamics are currently not well understood in the Klamath River estuary. In particular, suspended sediment concentrations entering and leaving the estuary are currently unknown, and the nutrient content of estuarine surface sediments has only been characterized at a single site during a single sampling event. Additional sediment nutrient information for the upper, middle, and lower estuary, as well as the south slough, would support better understanding of current nutrient dynamics in the estuary. Grain size distribution of estuarine surface sediments at multiple locations in the estuary is also currently unknown. Conceptual study plans described in Sections 5.1.6 and 5.1.7 address these data gaps.

3.4 Nutrients

3.4.1 Current Understanding

Nutrient data for the Klamath River estuary was collected as part of mainstem Klamath River studies and data sources are therefore summarized in Table 7. During June through September 2004, the Yurok Tribe, in conjunction with the North Coast Regional Water Quality Control Board (NCRWQCB), carried out the most extensive study to date of Klamath River estuary nutrient concentrations, including grab samples for total nitrogen [TN], nitrate [NO_3^-], nitrite [NO_2^-], ammonia [NH_4^+], TKN, total phosphorus [TP] and ortho-P, as well as bacteria (i.e., *E. coli*), chl-a, and *in situ* parameters (i.e., temperature, dissolved oxygen, pH, salinity) in the main channel at upper, mid- and lower estuarine locations (YTEP 2005). Study results indicated that levels of nitrogen were at or below reporting limits during the study period with only a few exceptions, and even the exceptions indicated low levels (<0.1 mg/L for NO_3^-, NO_2^-, and NH_4^+; < 1mg/L for TN and TKN). Levels of phosphorous were more variable, but were also generally low at <0.25 mg/L for TP and <0.05 mg/L for ortho-P. Chl-a samples were low at less than 0.01 mg/L, except on one date in late September when levels in the upper portion of the estuary were 0.019 mg/L. Overall, nutrient and chl-a levels in the estuary were equal to or slightly greater than those measured upstream at the Turwar Gage (~RM 7) and in the Klamath River upstream of the Trinity River confluence (RM 40.0). Additional results for 2007 are forthcoming, but preliminary results indicate similarly low nutrient and chl-a levels at locations sampled in the deep, main channel of the estuary (YTEP 2008b).

Modeling of nutrient dynamics in the Klamath River estuary has not yet been rigorously undertaken. The draft TMDL calibration report (Tetra Tech, *in prep*) includes an estuarine component using Environmental Fluid Dynamics Computer Code (EFDC), a 3-dimensional model used to simulate water and water quality constituent transport in a variety of complex water bodies, including vertically mixed shallow estuaries, lakes, and coastal areas (Kalin and Hantush 2003). EFDC-modeled nutrient parameters for the Klamath River estuary include nitrification rates, benthic flux rates for ortho-P and NH_4^+, and hydrolysis rates for particulate and dissolved forms of organic nitrogen, phosphorous, and carbon. For estuarine algae, the model includes rates of growth, respiration, and mortality, as well as settling velocities and optimal temperature ranges. The TMDL estuarine model component was calibrated using 2004 *in situ* temperature, dissolved oxygen and salinity, as well as grab samples for nutrients and chl-a at three sites in the lower, middle, and upper estuary (Tetra Tech, *in prep*).

While the draft TMDL estuary component has been developed, there have been no studies to determine whether nutrient availability currently controls algae and macrophyte growth in the estuary, and if so, what form of nutrients are limiting, or how primary productivity may affect other water quality parameters, such as dissolved oxygen and turbidity levels. Additionally, because the form and loading of nutrients released from the mainstem reservoirs to the lower Klamath River is not yet clearly understood, nor is the rate of cycling of these nutrients in the river, the form and loading of nutrients to the Klamath River estuary is still uncertain.

Further application of the EFDC portion of the TMDL model may prove useful for continued modeling of nutrient dynamics in the estuary, however additional calibration data should be incorporated (e.g., 2007) or collected if not yet available, and nutrient limitation should be assessed in the estuary to test underlying assumptions of the model. Additionally, results of separate 2-dimensional sediment transport modeling for the estuary may be useful to compare with EFDC, as the sediment routine in EFDC is relatively unsophisticated (Kalin and Hantush 2003) and may not sufficiently describe sediment dynamics in relation to nutrient cycling the Klamath River estuary.

3.4.2 Impacts of Dam Removal

3.4.2.1 Short-term Effects

The possibility of short-term sediment deposition in the Klamath River estuary requires further study (Section 3.3.2.1). Significant deposition of sediments containing 3 to 5% organic material in the estuary may affect short-term nutrient cycling as carbon, nitrogen, and phosphorus availability may increase in the relatively low-nutrient estuary. However, if newly deposited sediments are displaced by subsequent high flows or actively removed from the estuary within the 1–2 years following dam removal, the effect on nutrient dynamics in the estuary may be only temporary.

At present, no short-term effects on Klamath River estuary levels of inorganic nutrients such as nitrate (NO_3^-), ammonium (NH_4^+), and ortho-P are anticipated. However, the form and loading of nutrients to the Klamath River estuary under a dam removal scenario is highly uncertain because nutrient form and loading under current conditions is not yet well understood. A re-assessment of short-term effects on inorganic nutrient concentrations for the Klamath River estuary following dam removal should be undertaken following additional study of nutrient dynamics in the estuary itself.

3.4.2.2 Long-term Effects

Long-term deposition of sediment in the estuary may increase following dam removal, since the dams will no longer trap algae and sediment in upstream reaches (Section 3.3.2.2). Renewed transport of organic material from upstream will potentially affect long-term nutrient cycling and sequestration in the estuary. Increased carbon, nitrogen, and phosphorus content of sediments moving through, and potentially being deposited within, the Klamath River estuary may increase long-term rates of primary productivity, with possible ramifications for the estuarine food web.

However, the form and loading of nutrients to the Klamath River estuary under a dam removal scenario is highly uncertain because current conditions are not yet well understood.

3.4.3 Data Gaps

Multiple nutrient-related data gaps exist for the Klamath River estuary. It is currently unknown whether growth of algae and aquatic macrophytes in the estuary is limited by nutrients, and if so, the form of the limiting nutrient(s) (Section 3.4.1). Data gaps also include how primary productivity in the estuary affects dissolved oxygen and turbidity levels under both current conditions and a dam removal scenario. Additionally, because the form and loading of nutrients released from the mainstem reservoirs to the lower Klamath River is not yet clearly understood, nor is the rate of cycling of these nutrients in the river, the form and loading of nutrients transported to the Klamath River estuary is still uncertain. Conceptual study plans described in Sections 5.1.6 and 5.1.7 address these data gaps

3.5 Dissolved oxygen and pH

3.5.1 Current Understanding

Dissolved oxygen and pH have been monitored in the Klamath River estuary by CDFG (Wallace 1998) and most recently by USFWS (Hiner 2006) and the Yurok Tribe (YTEP), with support from the North Coast Regional Water Quality Control Board. Data sources for dissolved oxygen and pH data in the Klamath River estuary are summarized in **Table 11**.

Table 11. Dissolved oxygen and pH data sources for the Klamath River estuary.

Source	Description of Data	Dates available
Hiner 2006	Bi-weekly *in situ* dissolved oxygen at three cross sections and several other sites.	2001–2003
Wallace 1998	Monthly to bi-monthly dissolved oxygen data from at least four transects.	1991–1994
YTEP 2005	Sporadic summertime continuous dissolved oxygen and pH data at three sites on the surface and at depth. Surface and at depth measurements on four days for three cross sections.	2004
YTEP and NCRWQCB 2005	Continuous monitoring of dissolved oxygen at six sites during a pulse flow from the Trinity River in August.	2004

Dissolved oxygen concentrations in the Klamath River estuary vary both temporally and spatially. Dissolved oxygen concentrations measured in the deeper, main channel of the estuary are generally greater than 6 to 7 mg/L throughout the year (Hiner 2006, YTEP 2005). Low dissolved oxygen concentrations (<1 to 5 mg/L) have been observed during summer months in the relatively shallow, heavily vegetated south slough (Hiner 2006, Wallace 1998). The low levels of dissolved oxygen observed in the slough are likely due to high rates of growth and subsequent decomposition of algae and macrophytes, which are not abundant elsewhere in the estuary. Nutrient concentrations have not been reported for the water column or sediments of the south slough, and it is possible that a longer residence time encourages particulate deposition, increasing nutrient availability and consequently algal and macrophyte growth in this portion of the estuary. During 2003, when the majority of south slough dissolved oxygen data were collected, the projected surface area of the slough appeared to be a relatively small portion of the total projected surface area of the estuary (Figure 2, Hiner 2006).

pH levels in the estuary are generally between 7 and 9 (YTEP 2005). Diel variations in pH are typically on the order of 0.5 pH units, and fluctuations tend to be somewhat larger in the late summer and early fall. The draft EFDC estuary model component and observed data show very low algae concentrations (Tetra Tech *in prep*) and chl-a concentrations (YTEP 2005) in the estuary, suggesting that local photosynthesis and biological respiration are not causing significant diel fluctuations of dissolved oxygen or pH. If significant diel fluctuations of dissolved oxygen or pH are observed, they are likely to be caused by an upstream diel signal that is subsequently transported into the estuary.

3.5.2 Impacts of Dam Removal

3.5.2.1 Short-term Effects

Short-term effects of dam removal on dissolved oxygen and pH in the estuary are not expected to occur since short-term hydrology and nutrient cycling, which directly effect dissolved oxygen and pH levels, are not likely to be impacted by dam removal. However, since estuary-specific sediment dynamics have not been thoroughly investigated (Section 3.3.2), further study is required to confirm this assumption. Significant sediment deposition in the estuary could affect the formation of the sand berm, causing longer duration or earlier mouth closure in the short-term, and consequently longer periods of low dissolved oxygen in the shallow, heavily vegetated south slough. Since overall levels of primary productivity in the estuary appear to be low, dissolved oxygen and pH levels in the main estuary channel are not expected to be altered in the short-term.

3.5.2.2 Long-term Effects

While existing water quality modeling efforts for a no-dam scenario predict increased diel dissolved oxygen variation in the Klamath River as far downstream as the Trinity River confluence (RM 40.0) (PacifiCorp 2005a), no analysis has been conducted for the Klamath River estuary. However, the large distance between the Project Reach and the Klamath River estuary (approximately 190 miles) means that the anticipated effects of dam removal on algal growth, dissolved oxygen, and pH just downstream of the Project Reach are not likely to translate to the estuary. Instead, long-term changes in estuarine morphology, nutrient supply and primary productivity resulting from dam removal (see Sections 3.1 through 3.4) will be important factors determining impacts to dissolved oxygen and pH, and in particular low-flow summertime conditions and the frequency and duration of mouth closure. Increased long-term nutrient supply and sequestration in the estuary and increased incidence of mouth closure during summer months could increase primary productivity and community respiration and correspondingly increase diel dissolved oxygen swings, and potentially result in episodic low dissolved oxygen. However, since the effects of removing the Project dams on estuarine morphology and nutrient supply are still largely unknown, alterations to dissolved oxygen and pH are also uncertain. Significant diel fluctuations of dissolved oxygen or pH caused by an upstream diel signal that is subsequently transported into the estuary will decrease in the long-term if the incidence of large algal blooms on the lower Klamath River is decreased as a result of dam removal.

3.5.3 Data Gaps

Data gaps for dissolved oxygen and pH regimes in the estuary are similar to those identified for estuarine morphology, algae growth and nutrient cycling, as they are linked. While the draft TMDL estuary component has been developed, there have been no studies to determine whether nutrient availability currently controls algae and macrophyte growth in the estuary, and if so, what form of nutrients are limiting, or how primary productivity may affect dissolved oxygen and pH. The conceptual study plan described in Section 5.1.7 addresses these data gaps

3.6 Algae

3.6.1 Current Understanding

Available data on algal populations in the Klamath River estuary is generally limited to phytoplankton surveys conducted for monitoring *Microcystis aeruginosa* levels (YTEP 2006, 2007, and 2008a), but recent monitoring by the Yurok Tribe has resulted in additional algal species information (YTEP 2007 and 2008a). Based on 2006 and 2007 data, algal composition in the estuary is generally similar to that observed in the lower Klamath River, with diatoms and blue-green algae as the dominant species. Estuarine phytoplankton densities are generally lower than concurrently measured phytoplankton densities upstream in the lower Klamath River. The exception to this was a single density sample collected on June 12, 2007 that was several times greater than that observed at any other site during the summer and was dominated by the diatom species *Diatoma tenue* and *Nitzschia frustulum*. *Microcystis aeruginosa* concentrations in the estuary exceeded the Yurok Tribe posting action level (40,000 cells/mL) by more than a factor of 2 on one occasion in September 2007, and exceeded the WHO guideline for low risk recreational use (20,000 cells/mL) in one additional instance in September 2005. The 2005 and 2007 elevated levels of *Microcystis aeruginosa* corresponded with elevated levels measured further upstream in the lower Klamath River, indicating that *Microcystis aeruginosa* was being transported into the estuary from the lower river. Periphyton data collected in the estuary is unavailable, likely because much of the estuary is fairly deep. However, abundant periphyton cover has been observed in the south slough (Hiner 2006).

3.6.2 Impacts of Dam Removal

3.6.2.1 Short-term Effects

Short term effects of dam removal on algae in the estuary are not likely to differ substantially from long-term effects, described below.

3.6.2.2 Long-term Effects

Because limited information is available to describe the current conditions of Klamath River estuarine algal biomass, population dynamics, and the likelihood of nutrient limitation on algal growth, the potential effects of removing the Project dams on algae in the estuary are uncertain. Removal of the Project reservoirs will likely reduce or eliminate elevated *Microcystis aeruginosa* levels within the estuary, as observations of this algal species indicates that it is likely transported downstream from the mainstem Klamath River, including the Project reservoirs (Section 2.6.1.1). The same may be true of other blue-green or diatom phytoplankton species, such as *Diatoma tenue* and *Nitzschia frustulum*, previously observed in the estuarine water column. Long-term effects of removal of the Project dams on estuarine nutrient levels are still uncertain, but if nutrients are limiting algal growth in the estuary then alterations to overall nutrient cycling will effect algal growth as well.

3.6.3 Data Gaps

Current understanding of algal biomass, population dynamics, and possible nutrient limitation of algal growth is limited for the Klamath River estuary and thus represents an existing data gap. Study Plans 5.1.8 and 5.1.9 address the lack of information regarding the estuarine algal dynamics and the contribution of primary productivity to estuarine nutrient cycling.

3.7 Summary of potential effects of the removal of Iron Gate, Copco 1, Copco 2, and J.C. Boyle dams on Klamath River estuary water quality

Based on the general review of available information presented in Sections 1.1 through 1.5, the following is a summary of potential effects that removal of the four Project dams may have on hydrology and water quality of the Klamath River estuary:

- Currently, the Project dams are not likely to impact estuarine hydrology on an annual basis, however it is not well understood if small changes in summertime low-flow conditions due to current dam operations or potential dam removal will alter estuarine hydrology sufficiently to affect mouth closure dynamics and estuary water temperatures.
- High suspended sediment loads are expected in the lower Klamath River and the estuary for the first few years (1–2 years) following potential dam removal, which in addition to causing high TSS (>300 mg/L) and turbidity in the water column, may alter estuarine sediment deposits, the frequency and duration of mouth closure, and potentially reduce the volume of the cooler salt water wedge that periodically forms during summer months.
- Currently, water quality conditions in the estuary main channel indicate relatively low productivity, as evidenced by low algal and macrophyte growth, small diel fluctuations in dissolved oxygen and pH, and low nutrient concentrations in the water column. However, nutrient dynamics in the estuary and in the mainstem Klamath River are currently not well understood.
- Although a single sediment core recently sampled from the estuary main channel indicated low carbon and nitrogen content and a relatively low content of phosphorus, nutrient cycling in the estuary may be altered by dam removal and subsequent deposition of sediments containing higher levels of sediment-associated nutrients as found in upstream reservoir deposits.

4 POTENTIAL IMPACTS OF CLIMATE CHANGE ON KLAMATH RIVER WATER QUALITY

4.1 Current Understanding

The potential impacts of global climate change on water quality in the mainstem Klamath River and the Klamath River estuary are based upon current estimates of changes in air temperature and precipitation patterns for the California North Coast hydrologic region (as defined by CDWR [1998]). Regional climate models estimate an increase in median annual air temperature of 3 ºC (5 ºF) by 2050, with the greatest peaks occurring in January, February, March, and May (> 3 ºC [5 ºF]) (Snyder et al 2004). Higher air temperatures from January to March support predictions of considerable decreases in snow pack, with snow accumulation ceasing nearly a month earlier than historical trends (February vs. March), and an earlier, more modest spring runoff peak. While future predicted precipitation amounts for the North Coast hydrologic region are similar to contemporary levels, a greater proportion is expected to fall as rain rather than snow, resulting in greater runoff earlier in winter than under current conditions (Kiparsky and Gleick 2003, Snyder et al. 2004). Less snow accumulation may also decrease surface reflectivity (albedo) and increase surface absorption of solar radiation, leading to even higher air temperatures and less accumulated snow (Snyder et al 2004). Interestingly, glaciers atop Mount Shasta, located in a watershed adjacent to the Klamath River Basin, have expanded over the last half century due to increases in precipitation driven by medium-term climatic cycles (see El Niño Southern Oscillation discussion below) (Howat et al. 2007). However, in-kind precipitation increases over the next century are not expected to offset predicted natural and anthropogenically driven climate warming, resulting in the extreme contraction or near total loss of nearby Mount Shasta glaciers by 2100.

Changes in climatic variables have been detected recently in the Klamath River basin. Snow water equivalent (SWE), or the amount of water stored in the basin as snow, decreased significantly from 1942–1976 to 1977–2005 in sub-basins lower than 1,800 m (5,900 ft) elevation (Van Kirk and Naman 2008). Correspondingly, these sub-basins exhibited lower late summer baseflow. The SWE data agree with California regional climate models that predict decreased snowfall (20–40%) but greater winter rainfall (>150%) for elevations below 2,500 m (8,200 ft) (Kim 2001). Water temperatures also increased along the middle and lower Klamath River by 0.5 ºC (1 ºF) per decade from 1962–2000, with temperatures warming earlier in spring and staying warm longer into fall (Bartholow 2005). The length of the mainstem Klamath River with temperatures suitable for salmonids decreased by 8.2 km (5 mi) per decade over the same period (Section 2.2.1).

However, the available data do not confirm global climate change impacts to SWE and water temperatures in the middle and lower Klamath River system because data analyzed by Van Kirk and Naman (2008) and Bartholow (2005) span crossover periods within the Pacific Decadal Oscillation (PDO). The PDO is a recurring pattern in northern Pacific Ocean temperatures occurring over decadal time scales that alternates between cool cycles, associated with high snowpack and elevated streamflow, and warm cycles, associated with less snowpack and decreased streamflow. An inflection point from a cool to a warm cycle appears to have occurred in 1977 (Mantua et al. 1997) and recent evidence suggests another cool cycle may have begun as early as 1998 (Mantua 1997, ISAB 2007). As such, observed SWE decreases and water temperature increases over the periods of record (1977–2005, 1963–2000) in the Klamath River basin may have been driven by PDO effects. While these two variables may show opposite trends during the next cool cycle, if global climate model (GCM) and regional climate model

(RCM) climate change predictions are reasonably accurate, the succeeding warm phase of the PDO may bring greater extremes in SWE and water temperature for the Klamath River basin.

The El Niño Southern Oscillation (ENSO) further complicates the detection of long-term climate change effects for the middle and lower Klamath River and elsewhere along the Pacific Coast. In the Pacific Northwest, ENSO produces predominantly cool and dry weather, with events lasting 6–18 months, and complete cycles building and declining over a 2–7 year period (ISAB 2007). With continued global warming, the frequency of ENSO events may increase and/or the variation between ENSO and non-ENSO events may become more extreme (Kiparksy and Gleick 2003). Along the California Coast, the difference between average ENSO and non-ENSO floods is greatest in southern California, and becomes less pronounced in a northerly direction (Andrews et al. 2004). Currently, basins such as the Klamath River, which are north of 41 ºN, display lower flood peaks during ENSO conditions, likely reflecting influence of a low pressure cell covering the Pacific Northwest that shifts the winter storm track to the south (NOAA 2008c). However, the Klamath River basin is at the southern edge of this low pressure cell and any northward shift in the cell may considerably change the ENSO hydrograph by exposing the basin to wet winter storms more characteristic of southern California.

The current ambiguity in the ENSO response to global climate change and the need for further resolution of PDO cycle length and frequency means that predicting water quality conditions in the Klamath River with respect to global climate change is still highly uncertain. If future predictions of higher levels of rainfall, rather than snow, hold true, greater runoff and associated turbidity and TSS levels would be expected earlier in winter as compared with current conditions. This would likely increase the number of days each year when the river exhibits sediment-induced high turbidity and TSS, and may increase particulate phosphorous delivery to the river. Higher water temperatures would also likely be supported due to the lack of spring snowpack.

4.2 Data Gaps

The TMDL in development (NCRWQCB 2008) does not address the effects of global climate change. Implementation of modeling scenarios in the Klamath River that account for future climate change will be necessary to create appropriate management strategies.

5 RECOMMENDED CONCEPTUAL STUDY PLANS

The following study plans have been designed to fill data gaps related to knowledge of hydrology, morphology, sediment, water quality and algal dynamics in the lower Klamath River and the Klamath River estuary. The study plan elements have a dual purpose; to supply information supporting informed decision making surrounding the potential removal of Iron Gate, Copco 1 and 2, and J.C. Boyle dams on the mainstem Klamath River, as well as provide baseline data for determining the possible effects of dam removal on the lower river and estuary, should the dams eventually be removed. All study plans are presented at a conceptual level of detail and are focused on the effects of dam removal on water quantity and/or quality in the lower Klamath River and estuary. Since water quality is linked to fish species health, related studies focusing on the biotic response to potential changes in water quality should also be undertaken, although inclusion of these elements is beyond the scope of this technical memo. The recommended water quality studies presented below will benefit from expansion and refinement following comments and insights from the Klamath Decommissioning Investigations Group and the larger regulatory and scientific community involved in the current consideration of dam removal. To support continued coordination between the multiple organizations involved in Klamath River water quality data collection and analysis (see Section 1), all proposed study plan schedules include presentation of preliminary and/or final results at Klamath River Water Quality Management Coordination Group (KRWQMCG) semi-annual meetings.

5.1.1 Conceptual Study Plan 1. Turbidity and suspended sediment monitoring in the mainstem Klamath River.

5.1.1.1 Purpose

The purpose of this recommended study element is to better characterize turbidity and suspended sediment (both total and volatile) in the mainstem of the Klamath River to allow for a better understanding of current conditions and the impacts of the dams on water quality and beneficial uses. The data will also serve as baseline information should the dams be removed.

5.1.1.2 Approach

The approach involves continuous and discrete sampling of turbidity and suspended sediment concentrations at multiple locations and across seasons in the mainstem Klamath River and the Klamath River estuary.

Recommended study elements include the following:

- Determination of the optimal methodology and seasonal timing of sampling to characterize suspended sediment and turbidity in the mainstem and estuary. The study design should ensure that sufficient data is collected during seasonal peaks in turbidity and suspended sediment, which may be partially achieved through the turbidity threshold sampling (TTS) method developed to capture high wintertime turbidity event signals (Lewis 2003). An adaptation of the TTS methodology to trigger TSS sampling during summertime high turbidity, low flow events could allow for efficient sampling of algal-dominated TSS events.
- Inclusion of volatile suspended sediment (VSS) measurements with total suspended sediment (TSS) to potentially isolate algal-dominated TSS signals from primarily mineral-derived signals.

- Coordination with ongoing turbidity and TSS sampling conducted by tribes and PacifiCorp.
- Baseline monitoring over a minimum of two years to characterize seasonal turbidity and suspended sediment levels above, within, and below the Project Reach and at multiple locations in the mainstem river downstream of the dams.
- Data analysis to determine primary sources of turbidity and suspended sediment to the middle and lower Klamath River and the estuary, the likely effects of dam removal on these sources, and potential impacts to water quality and beneficial uses from changes in suspended sediment levels due to dam removal.
- Implementation of adaptive techniques to target sampling locations and events of interest.
- Should the dams be removed, continuation of monitoring following dam removal to determine the impacts on turbidity and suspended sediment.

5.1.1.3 Schedule

Table 12. Conceptual study plan 1 proposed schedule.

Proposed Task	Timing
Determine optimal sampling methodology, including potential for VSS component	Spring 2009
Conduct monitoring	Summer 2009 – Spring 2011
Annual reports	Spring, annually

5.1.2 Conceptual Study Plan 2. Determine baseline productivity estimates and growth limiting factor(s) for aquatic macrophytes and periphyton in the mainstem Klamath River downstream of the Project dams.

5.1.2.1 Purpose

The purpose of this study is to describe current periphyton and aquatic macrophyte growth in the middle and lower Klamath River downstream of the Project Reach in order to better support predictions of dam removal effects on long-term primary productivity and to serve as baseline data should the dams be removed.

5.1.2.2 Approach

The approach focuses on field survey data collected to determine biomass estimates of seasonal periphyton and aquatic macrophytes in the Klamath River as an estimate of baseline productivity, and nutrient limitation assays to improve the understanding of factors controlling riverine primary productivity. The following recommended study elements could co-occur with ongoing water column nutrient sampling currently conducted by the Yurok Tribe or PacifiCorp, but may require additional sampling locations to best characterize periphyton and aquatic macrophyte distribution.

- Conduct periphyton and aquatic macrophyte biomass surveys along transects in the middle and lower Klamath River. Samples should be collected monthly from July through October, and once each during January and April. For aquatic macrophytes and periphyton, quadrant sampling along a transect should be used. Sample analysis should include species composition, wet weight, dry weight, and nutrient content (i.e., TN, TP).

- Conduct experimental nutrient limitation studies for algal and macrophyte growth, including determination of what form of nutrients may be limiting primary productivity (e.g., NO_3^-, NH_4^+, organic N, ortho-P),

The nutrient limitation assays could be coordinated with the study of limiting factors for *C. shasta* (Section 5.1.3), because the latter would include determination of nutrient limitation for *Cladophora* spp. growth in the Klamath River.

5.1.2.3 Schedule

Table 13. Conceptual study plan 2 proposed schedule.

Proposed Task	Timing
Conduct periphyton and aquatic macrophyte biomass surveys	Beginning in summer 2009, monthly surveys for at least 2 years, from July through October, and once each during January and April
Conduct experimental nutrient limitation studies	Concurrent with above task
Draft report	Fall 2011/Winter 2012
Presentation of preliminary results at KRWQMCG Meeting	Fall 2011/Winter 2012
Final report	Spring 2012

5.1.3 Conceptual Study Plan 3. Determine conditional and temporal trends of and effect of river regulation on *M. speciosa* habitat area and population abundance, and *C. shasta* infection rate and concentration

5.1.3.1 Purpose

The purpose of this study is to describe *M. speciosa* habitat area and population abundance within the mainstem Klamath River, and to test effects of flow and temperature on *M. speciosa* habitat area and population abundance to better support predictions of effects of river regulation on *M. speciosa* habitat and potential *C. shasta* abundance, and to serve as baseline data should dam removal occur.

5.1.3.2 Approach

The approach focuses on field surveys in the middle and lower Klamath River to describe current *M. speciosa* habitat and population abundance, and mesocosm experiments that test the effects of discharge, temperature, and nutrient limitation on *M. speciosa* habitat and population abundance, and *C. shasta* infection rate and water column concentration. This study follows methods and conclusions developed elsewhere (e.g., OSU [2004], Stocking and Bartholomew [2007]) and advances the study approach initiated by Bartholomew and Bjork (2007). The study is intended to test specific hypotheses regarding the effects of flow regulation on *M. speciosa* habitat and population abundance, and *C. shasta* infection rate.

Recommended study elements include the following:

- Sequential surveys of *M. speciosa* habitat and populations from mid- summer to fall, beginning after senescence and invertebrate predation have reduced *Cladophora* spp. from long filaments to 0.5–1 cm mats (see Section 2.6.1.2), and continuing as baseflows reach their minimum to determine conditional and temporal trends in *M. speciosa* habitat and population abundance;

- Concurrent surveys of in-stream temperature, infection rate of *M. speciosa* by *C. shasta*, and *C. shasta* spore concentration within the water column to detect conditional and temporal trends in infection rate;
- Comparison of *in situ* infection rates to those recently determined in laboratory studies conducted by Bartholomew and Bjork (2007);
- Surveys of *M. speciosa* habitat and populations within outdoor mesocosms hydrologically connected to the Klamath River, in which velocity, temperature, and nutrient concentration are experimentally controlled;
- Concurrent surveys of *C. shasta* infection rate and *C. shasta* spore concentration within the water column within outdoor within outdoor mesocosms hydrologically connected to the Klamath River, in which velocity, temperature, and nutrient concentration are experimentally controlled; and,
- Comparison of mesocosm infection rates to those recently determined in laboratory studies conducted by Bartholomew and Bjork (2007).

5.1.3.3 Schedule

Table 14. Conceptual study plan 3 proposed schedule.

Proposed Task	Timing
Field surveys of *M. speciosa* habitat and populations	At least 2 surveys beginning in mid- to late summer and ending in fall
Surveys of in-stream temperature and *C. shasta*	At least 2 surveys beginning in mid- to late summer and ending in fall to occur concurrently with above task
Mesocosm experiments on effects of velocity, water temperature, and nutrient limitation on *M. speciosa* habitat and populations	Fall 2009
Mesocosm experiments on effects of velocity, water temperature, and nutrient limitation on *C. shasta* infection rates	Fall 2009 to occur concurrently with above task
Draft report	Spring 2011
Presentation of preliminary results at KRWQMCG Meeting	Spring 2011
Final report	Fall 2011

5.1.4 Conceptual Study Plan 4. Perform focused analysis of existing data record to demonstrate linkages between observed algal blooms and nutrient pulses in the middle and lower Klamath River.

5.1.4.1 Purpose

The purpose of this study is to further examine the existing water quality data record for the middle and lower Klamath River to demonstrate linkages between observed large increases in suspended and attached algal biomass (i.e., blooms) and nutrient pulses. The proposed study focuses on observed nutrient pulses and algal blooms over the long-term data record, because clear identification of these relatively large changes in Klamath River water quality may allow for determination of causal linkages between nutrient concentrations, algal growth and decay, and associated physical water quality parameters such as dissolved oxygen and pH. Results would allow for the potential refinement of existing water quality models (e.g., TMDL, PacifiCorp), and they would also complement the application of these complex numerical models by supporting a better conceptual understanding of current nutrient and algal dynamics in the Klamath River among the general public who may not be well-versed in the complexities of water quality modeling

5.1.4.2 Approach

While a great deal of water quality data has been collected in the Klamath River Basin, attempts to analyze linkages between total nutrient (TN, TP) or bioavailable nutrient (i.e., TIN, NO_3^-, NH_4^+, ortho-P) concentrations and suspended and attached algal biomass are limited to subsets of the available data record. For example, Kann and Asarian (2007) analyze links between nutrient concentrations and phytoplankton biovolume in the Project reservoirs for May 2005 to May 2006, Eilers (2005) reports correlations between nutrient concentrations and periphyton growth in middle and lower Klamath River for September 2004, and Kier Associates (2006) use 2004 data to examine correlations between algal biomass and nutrient concentrations in the middle Klamath River. The results of the PacifiCorp (2005c) and Tetra Tech (*in prep.*) water quality models also provide insight into the linkages between various water quality indicators, but the models have been calibrated using limited subsets of the available data record. Thus far, no analysis has utilized the entire available set (1990 to 2008) of nutrient, algae, and associated *in situ* water quality data to attempt to link observed nutrient concentrations to algal blooms in the middle and lower Klamath River.

The approach involves identification of relatively large changes in nutrient concentrations or algal biomass (i.e., order of magnitude or otherwise notable) in the existing data record that are not attributable to changes in hydrology and that occur over relatively short time periods (on the order of weeks). Examples of such events include the increase in nutrient concentrations and algal biomass observed in the lower Klamath River in September 2007 (YTEP 2008b) and the increase in algal biomass in and immediately downstream of Iron Gate Reservoir (RM 190.1) observed in August and September 2002 (Kann and Asarian 2006). Where data is available to describe both nutrient concentration and algal biomass, such large changes provide an opportunity to determine if changes in nutrient concentrations appear to affect algal biomass. To augment the limited set of algal data, empirical relationships between algal biomass and pH and dissolved oxygen will be determined, so that the latter two parameters may be used as a proxy for algal biomass. The analyses will be structured to test the following hypotheses:

- Nutrient pulses released from the Project reservoirs stimulate algal growth in the middle and lower Klamath River.

- Periphyton growth in the middle and lower Klamath River is limited by inorganic nitrogen availability.

Recommended study elements include the following:

- Conduct temporal and spatial analysis of available nutrient and algae data throughout the Klamath River to identify large (i.e., order of magnitude or otherwise notable) changes in nutrient concentrations or periphyton and phytoplankton biomass, which are not attributable to hydrologic events.

- For each large change in algal biomass identified, examine antecedent, concurrent, and subsequent nutrient data over a period of days to weeks to determine if the observed increase in algal biomass coincides with an alteration in the concentration of nutrients, and specifically inorganic nitrogen.

- For each large change in nutrient concentration identified, examine antecedent, concurrent, and subsequent algal biomass data over a period of days to weeks to determine if biomass was apparently affected by the increased nutrient concentrations. Use temporal trends in these estimates of algal concentration to identify causal relationships between nutrient concentrations and algal biomass.

- If algal biomass is not available for the reaches in question, multivariate regression analysis may be used to establish an empirical correlation between measured instances of periphyton and phytoplankton biomass and corresponding dissolved oxygen and pH levels (mean values and the magnitude of diel fluctuations), so that dissolved oxygen and pH may be used as a proxy for algal biomass. In this case, for each large change in nutrient concentration identified, use antecedent, concurrent, and subsequent dissolved oxygen and pH data to estimate biomass of periphyton and phytoplankton. This effort will build upon previous work by Kier Associates (2006) and thus presents an opportunity to collaborate with the original authors of the approach.

- For each large change in nutrient concentrations, examine antecedent, concurrent, and subsequent nutrient data upstream to determine, the timing and general location (i.e., upper, middle, lower Klamath River) of the nutrient source. In order to address the second hypothesis, inorganic nitrogen will have to be specifically called out in the analysis.

The proposed study could also be conducted in cooperation with entities currently developing or refining existing water quality models for the Klamath River (e.g., NCRWQCB, PacifiCorp, Tetra Tech) so that output of the water quality model(s) could be compared with the expanded set of available Klamath River data to determine model ability to represent algal blooms and/or nutrient pulses.

5.1.4.3 Schedule

Table 15. Conceptual study plan 4 proposed schedule.

Proposed Task	Timing
Data compilation and synthesis	Spring/Summer 2009
Draft report	Summer 2009
Presentation of preliminary results at KRWQMCG Meeting	Spring 2009
Final report	Fall 2009
Presentation of final results at KRWQMCG Meeting	Fall/Winter 2009/2010

5.1.5 Conceptual Study Plan 5. Describe hydrology, morphology, and mouth closure dynamics of the Klamath River estuary

5.1.5.1 Purpose

The overall purpose of this study is to improve the understanding of estuarine hydrology, morphology, and mouth closure dynamics in order to better inform decision making regarding potential removal of the four Project dams. Specifically, this study element will characterize estuarine hydrology with respect to current mainstem dam operation as well as other tributary inputs, and will describe and link morphology and mouth closure dynamics to the various flow conditions analyzed.

5.1.5.2 Approach

The approach involves analysis of available flow data from a subset of upstream USGS gages (see list below) to determine annual and seasonal hydrology of the estuary as well as the relative contributions from 1) the mainstem Klamath River upstream of Iron Gate Dam, 2) the Shasta, Scott, and Salmon River tributaries, as a group, and 3) the Trinity River. Additionally, analysis of available current and historical data on estuarine morphology and flow will be used to link incidences of mouth closure to particular river flow conditions and, if possible, longshore transport processes and shoreline dynamics.

Table 16. USGS gages assumed to be relevant to the hydrology analysis.

Gage number	USGS descriptor
11516530	KLAMATH R BL IRON GATE DAM CA
11523000	KLAMATH R A ORLEANS
11530000	TRINITY R A HOOPA CA
11530500	KLAMATH R NR KLAMATH CA

Recommended study elements include the following:

- Define the extent of the Klamath River estuary spatially, hydrologically, and functionally, and from a historical perspective, using existing USGS flow information, bathymetry (including Summer 2008 data currently being collected by the Yurok Tribe), LiDAR (including Summer/Fall 2008 data to be collected by Green Diamond), and other relevant studies and reports.

- Quantify average monthly, seasonal, and annual flows to the Klamath River estuary from available sources, including an analysis of relative contributions from the mainstem Klamath River as well as the Shasta, Scott, Salmon, and Trinity River tributaries.

- Determine whether changes in monthly flow during summertime due to current dam operations significantly alter estuarine hydrology.

- Investigate existing information on longshore transport processes and shoreline dynamics for the northern California Coast in the vicinity of the Klamath River estuary.

- Define the relationship between incoming river flows and mouth configuration, estuary depth, and volume.

5.1.5.3 Schedule

Table 17. Conceptual study plan 5 proposed schedule.

Proposed Task	Timing
Data compilation and synthesis	Fall/Winter 2008
Presentation of approach at Klamath River Water Quality Monitoring Coordination Group (KRWQMCG) Meeting	Fall 2008
Draft report	Spring 2009
Presentation of preliminary results at KRWQMCG Meeting	Spring 2009
Final report	Summer 2009

5.1.6 Conceptual Study Plan 6. Model Klamath River Estuary sediment transport dynamics

5.1.6.1 Purpose

The purpose of this study is to improve understanding of sediment dynamics in the Klamath River estuary in order to better support predictions of dam removal effects on the estuary in the short-term (1–2 years following dam removal) and the long-term (> 2 years). This study component will estimate suspended sediment concentrations in the estuary during and following dam removal, whether sediment is expected to deposit in the estuary following dam removal and if so, where it is likely to deposit (i.e., near mouth, in the south slough, along margins, etc.) and for how long.

5.1.6.2 Approach

In cooperation with the Yurok Tribe and Green Diamond, available historical and contemporary (e.g., 2004, 2008) estuary bathymetry and LIDAR information will be applied to the development of a dynamic sediment transport model to characterize sediment transport in the Klamath River estuary. Results from recent dam removal scenarios investigated using DREAM-1 (Stillwater Sciences 2008) will be extended from Orleans (~RM 59) to the upstream end of the Klamath River estuary (~RM 4), and then used as input to the estuarine sediment transport model.

In order to determine the most appropriate dynamic sediment transport model for application to Klamath River estuary, a review and comparison of the sediment transport elements of the 3-dimensional EFDC model included as part of the existing draft TMDL (Tetra Tech *in prep*) and potentially applicable 2-dimensional sediment transport models is recommended. Pros and cons of each model type should be investigated and described, along with the justification for selection of the final modeling tool. This task is expected to require coordination with Tetra Tech and the North Coast Regional Water Quality Control Board, in order to fully capture assumptions behind application of EFDC to the Klamath River estuary for the draft TMDL.

Recommended study elements include the following:

- Characterize estuarine surface sediments for the upper, middle, and lower estuary, as well as the south slough, including grain size distribution, organic carbon, nitrogen and phosphorus content (see Study Plan 4, Section 5.1.7), to serve as 1) calibration data for the current conditions dynamic sediment transport model, and 2) a sediment deposition baseline should the dams eventually be removed.

- Model estuarine sediment transport based on finalized dam removal simulation under various drawdown alternatives to determine likelihood of sediment deposition in the estuary and location of deposition (i.e., near mouth, in the south slough, along margins, etc.) for given drawdown alternatives.
- Using information regarding morphology and mouth closure dynamics developed under recommended Study Plan 4 (Section 5.1.5), evaluate whether sediment deposition during or after potential dam removal is expected to 1) decrease overall depth and volume of the estuary for average monthly, seasonal, and annual flows (and therefore reduce summertime intrusion of the cool salt wedge into the lagoon), or 2) affect the formation of the sand berm, causing longer duration or earlier mouth closure.

5.1.6.3 Schedule

Table 18. Conceptual study plan 6 proposed schedule.

Proposed Task	Timing
Compile existing bathymetry and LIDAR data and review various sediment transport model options	Winter 2008/Spring 2009 (dependent on when bathymetry and LIDAR data are available)
Develop dynamic flow model components	Winter 2008
Run model simulations	Spring 2009
Draft report	Spring 2009
Presentation of preliminary model results at KRWQMCG Meeting	Spring 2009
Final report	Summer 2009

5.1.7 Conceptual Study Plan 7. Improve understanding of Klamath River Estuary salinity, temperature, dissolved oxygen, pH, and habitat availability

5.1.7.1 Purpose

The purpose of this study is to characterize the temporal and spatial extent of suitable habitat for rearing salmonids in the Klamath estuary using *in situ* water quality comparison with habitat suitability criteria. In combination with results for Conceptual Study Plans 7 and 8, this study will enable evaluation of potential effects of dam removal on salmonid habitat availability in the estuary.

5.1.7.2 Approach

The dataset describing *in situ* water quality parameters in the Klamath estuary is too limited to reliably estimate the extent and quality of habitat for salmonids. In particular, continuous monitoring data is limited to several weeks in 2004 (Yurok Tribe 2005). We recommend deployment of continuous water quality monitoring sondes in a range of locations throughout the estuary, particularly in the summer months when water quality conditions are poor. These instruments should be deployed at stations throughout the estuary, and should include instruments deployed at depth to capture conditions in the salt wedge. Instruments should also be deployed in the south slough portion of the estuary, which may provide valuable habitat for juvenile out-migrants but where habitat may be limited by low dissolved oxygen levels (Hiner 2006). Concurrent with deployment of continuous water quality monitoring instruments, *in situ* water quality profiles should also be measured at a range of tidal stages and riverine flows.

Recommended study elements include:

- Based on habitat surveys, estimate the areal extent of hard, rocky surfaces within the estuary as compared with sandy or muddy intertidal sediment area, to support investigation of the potential for nitrification and denitrification in Klamath River estuarine substrates other than benthic sediments, including benthic and intertidal rocky biofilms (Study Plan 7, Section 5.1.8).
- Continuous *in sit*u monitoring of temperature and salinity at five locations in the estuary at the surface and at depth: the lower, middle, and upper estuary sites described in (Yurok Tribe 2005), and two additional sites in the upper and lower zones of the south slough.
- Concurrent with continuous *in situ* monitoring, measure *in situ* profiles of basic water quality parameters at a variety of tidal stages and riverine flows.

5.1.7.3 Schedule

Table 19. Conceptual study plan 7 proposed schedule.

Proposed Task	Timing
Estimate the areal extent of rocky and sandy/muddy surfaces within the estuary	Spring 2009
Continuous *in sit*u monitoring of temperature and salinity and *in situ* profiles of basic water quality	Spring 2009 through at least 3 years
Annual reports	Ongoing
Presentation of annual data at KRWQMCG Meeting	Ongoing

5.1.8 Conceptual Study Plan 8. Improve understanding of Klamath River Estuary nutrient dynamics

5.1.8.1 Purpose

The purpose of this study is to improve the understanding of nutrient dynamics in the Klamath River estuary in order to better support predictions of dam removal effects on the estuary in the long-term.

5.1.8.2 Approach

As discussed in Section 3.4, the form and loading of nutrients to the Klamath River estuary under a dam removal scenario is highly uncertain. In order to improve knowledge about nutrient form and loading under current conditions, and to provide baseline information should the dams eventually be removed, the recommended nutrient dynamics study approach is to collect water column nutrient samples to supplement the two seasons (e.g., June through September 2004 and 2007) of nutrient data that have been reported for the Klamath River estuary thus far (see Section 3.4, YTEP 2005, YTEP 2008). Additionally, the recommended study includes determination of nutrient fluxes across the estuarine sediment-water interface under different seasonal conditions. The nutrient flux information will serve as 1) further calibration data for the current EFDC sediment and nutrient dynamics model, and 2) a baseline for nutrient flux rates in estuarine sediments should the dams eventually be removed. Seasonal rates can be measured using sediment cores which are collected from locations in the upper, middle, and lower estuary, as well as the south slough, and maintained in the laboratory as remote chemostatic flux chambers.

Recommended study elements include the following:

- Conduct a literature review to investigate the potential for nitrification and denitrification in Klamath River estuarine substrates other than benthic sediments, including benthic and intertidal rocky biofilms, which may foster significantly different rates of nitrification and denitrification (Magalhães 2003, 2005). If results suggest these substrates may play a significant role in nutrient cycling in the Klamath Estuary, conduct additional measurements of nutrient fluxes on these substrates.
- Collect monthly samples for TN, NO_3^-, NO_2^-, NH_4^+, TKN, TP, and ortho-P, as well as bacteria (i.e., *E. coli*), chl-a, and *in situ* parameters (i.e., temperature, dissolved oxygen, pH, salinity). Sample sites should include the Turwar Gage, upper, middle, and lower estuary, and ocean sites sampled during 2004 and 2007 YTEP surveys, as well as one or several sites in the south slough portion of the estuary. Samples should be collected both in the surface freshwater layer and the bottom salt water layer when the estuary is stratified. Analysis of loading can be conducted using USGS gage 11530500.
- Sampling should be prioritized as follows: 1) frequency of sampling, particularly in August, September, and October, 2) Increased number of surface samples, and 3) surface and bottom sampling.
- Characterize estuarine surface sediments for the upper, middle, and lower estuary, as well as the south slough, including organic carbon, nitrogen, and phosphorus content and grain size distribution, (see Study Plan 3, Section 5.1.6), to serve as 1) further calibration data for the current EFDC sediment and nutrient dynamics model, and 2) a baseline for nutrient content in sediments should the dams eventually be removed.
- Conduct laboratory measurements of estuary sediment cores sampled and maintained as remote chemostatic flux chambers to determine nitrification, denitrification, and mineralization rates of sediments, as well as fluxes of ortho-P.
    - Collect cores at sufficient replication (i.e., minimum of 3 cores per location and/or treatment).
    - Maintain cores under varying conditions to simulate seasonal water quality differences in estuarine salinity and water temperature.
    - Include consideration of the effects of benthic primary producers and infauna to sediment flux rates in the study design (Dalsgaard et al. 2000).

5.1.8.3 Schedule

Table 20. Conceptual study plan 8 proposed schedule.

Proposed Task	Timing
Collect monthly water column nutrient, bacteria (i.e., *E. coli*), chl-a, and *in situ* parameters (i.e., temperature, dissolved oxygen, pH, salinity).	Spring 2009 through at least 3 years
Annual reports for monthly water column data	Ongoing
Presentation of annual data at KRWQMCG Meeting	Ongoing
Characterize surface sediments for nutrient content and grain size distribution	Summer 2009
Conduct laboratory experiments using estuarine sediment cores as chemostatic flux chambers	Spring 2009-Spring 2011
Literature review to investigate the potential for nitrification and denitrification in estuarine rocky substrates	Spring/Summer 2009
Draft report	Summer 2011
Presentation of preliminary laboratory experimental results at KRWQMCG Meeting	Fall 2011
Final report	Winter 2011

5.1.9 Conceptual Study Plan 9. Determine baseline productivity estimates and growth limiting factor(s) for aquatic macrophytes and algae in the Klamath River estuary

5.1.9.1 Purpose

The purpose of this recommended study element is to describe current algal and macrophyte growth in the Klamath River estuary in order to better support predictions of dam removal effects on long-term primary productivity and to serve as baseline data should the dams be removed.

5.1.9.2 Approach

The approach focuses on field survey data collected to determine the biomass of seasonal algae and aquatic macrophytes in the Klamath River estuary as an estimate of baseline productivity, and nutrient limitation assays to improve the understanding of factors controlling primary productivity. The recommended study elements could co-occur with the water column nutrient sampling described in Study Plan 7 (Section 5.1.8).

Recommended study elements include the following:

- Conduct algal and macrophyte biomass surveys along transects in the upper, middle, lower estuary and the south slough. Samples should be collected monthly from July through October, and once each during January and April. For aquatic macrophytes or macro algae, quadrant sampling along a transect should be used, while algal samples may require grab samples or boat tows. Sample analysis should include species composition, wet weight, dry weight, and nutrient content (i.e., TN, TP).
- Conduct experimental nutrient limitation studies for algal and macrophyte growth in the estuary, including determination of what form of nutrients may be limiting primary productivity (e.g., NO_3^-, NH_4^+, organic N, ortho-P),

5.1.9.3 Schedule

Table 21. Conceptual study plan 9 proposed schedule.

Proposed Task	Timing
Conduct algal and macrophyte biomass surveys	Beginning in summer 2009, monthly surveys for at least 2 years, from July through October, and once each during January and April
Conduct experimental nutrient limitation studies	Concurrent with above task
Draft report	Fall 2011/Winter 2012
Presentation of preliminary laboratory experimental results at KRWQMCG Meeting	Fall 2011/Winter 2012
Final report	Spring 2012

5.1.10 Conceptual Study Plan 10. Develop water quality conceptual model for assessing climate change impacts to the Klamath River.

5.1.10.1 Purpose

The purpose of this recommended study element is to further the assessment of potential impacts of climate change on the middle and lower Klamath River, including a dam removal scenario, to set the stage for basin-scale numerical modeling when downscaled regional climate change information becomes available for the Klamath Basin.

5.1.10.2 Approach

The approach involves application of climate change variables (i.e., air temperature, precipitation patterns) to existing water quality conceptual models, or to a new conceptual model (if necessary).

Recommended study elements include the following:

- Review existing water quality conceptual models for the Klamath River, including the final TMDL conceptual models for nutrients and water temperature and the conceptual model for nutrient enrichment and water quality impairment of fish habitat developed in Kier Associates (2006) to determine the most appropriate framework for assessing climate change impacts to water quality under current conditions and dam removal scenarios. This task should involve coordination with NCRWQCB and independent researchers to ensure conceptual (and potentially, numerical) model efforts are not duplicated.
- Develop “current conditions”, “future conditions without dam removal” and “future conditions with dam removal” conceptual models using existing frameworks (if appropriate) or a newly developed framework (if necessary) to include the Klamath Basin-specific effects of climate change on water quality.
- Identify if basin-scale numerical modeling efforts are prudent based on the availability of downscaled regional climate change information for the Klamath Basin.

5.1.10.3 Schedule

Table 22. Conceptual study plan 10 proposed schedule.

Proposed Task	Timing
Review of existing models and coordination with agencies and individual researchers currently working with water quality models of the Klamath River	Spring 2009
Application of climate change variables to conceptual water quality models	Summer 2009
Draft report	Fall 2009
Presentation of preliminary results at KRWQMCG Meeting	Fall 2009
Final report	Spring 2010

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